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An Application and Refinement of the Karst Disturbance Index through Evaluating Variability in Island Karst Disturbance in Puerto Rico

Brandon Lee Porter
Western Kentucky University, brandon.porter@wku.edu

AN APPLICATION AND REFINEMENT OF THE KARST DISTURBANCE INDEX THROUGH EVALUATING VARIABILITY IN ISLAND KARST DISTURBANCE IN PUERTO RICO

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Director of Thesis

Patricia Kambesis

Richard A. Bowker Dec. 15, 2010

Dean, Graduate Studies and Research Date

Dedication

To all my friends and family who have supported my efforts and provided me with much needed laughter. I would first like to dedicate this work to my mom, Carol Porter. Without her continued guidance, friendship, patience, love, and wisdom I would not be where I am today. Words are not enough to express how much I love you and appreciate all that you have done and put up with. Thank you for believing in me and lending me your confidence in my abilities when I was overwhelmed. I would also like to thank my dad, Marlin Porter, who helped shape my character, allowing me to persevere through hard times and never give up on something I start. Finally, I would also like to dedicate this work to my little sister, Nikki Porter. I have no doubt that you will far exceed my accomplishments someday and I love you very much.

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Directed by: Dr. Jason S. Polk

Department of Geography and Geology Western Kentucky University

Karst environments are unique landscapes that contain important resources, including freshwater aquifers and specialized ecosystems, which are easily disturbed due to the interconnected nature of the surface and subsurface. The anthropogenic impacts on karst are deleterious to the ecosystems that are dependent on the karst environment and also to groundwater supplies. The Karst Disturbance Index (KDI) is a holistic tool used to measure anthropogenic impacts associated with karst environments, which has been applied and refined through studies performed in Florida and Italy, yet still remains untested and susceptible to modification for other areas. Application of the KDI in Arecibo, Puerto Rico, which is geographically isolated, and highly vulnerable due to its sensitive karst resources, provides an opportunity to test the index in an island setting. This research resulted in two KDI scores for the study area using both the original and recently modified methods. The scores reflect a significant to severe disturbance to the municipality's karst environment of 0.54 and 0.68, respectively. Issues regarding the KDI were found from the application and comparison of these methodologies and revealed the need for adding additional indicators, including Mogote Removal and Coastal Karst, as well as several additional refinements and recommendations pertaining to scale, weighting, and incorporating the two methods together to create a single, more practical

KDI tool. The disseminated results of the assessment of the area using the KDI will educate and help to foster stewardship of this vital resource in Puerto Rico.

Resumen

Los ambientes karst son paisajes únicos que contienen recursos importantes, como acuíferos de agua fresca y ecosistemas especializados, los cuales son fácilmente trastornados debido a la natural interconexión entre la superficie y el subsuelo. Los impactos humanos en áreas karst son perjudiciales para los ecosistemas que dependen del ambiente karst, así como para las fuentes de agua subterráneas. El Índice de Trastorno Karst (KDI, por sus siglas en ingles) es una herramienta holística utilizada para medir los impactos antropogénicos asociados a los ambientes karst, el cual ha sido aplicado y perfeccionado por medio de estudios conducidos en Florida e Italia, pero que todavía permanece sin ser puesto a prueba y susceptible a modificaciones para otras regiones. La aplicación del KDI en Arecibo, Puerto Rico, un área geográficamente aislada y altamente vulnerable debido a la sensibilidad de sus recursos karst, provee una oportunidad para probar el índice en un entorno insular. Este estudio dio como resultado dos puntajes KDI para el área de estudio utilizando tanto el método original como el recientemente modificado. Los puntajes reflejan un trastorno significativo a severo en el ambiente karst de la municipalidad de 0.54 and 0.68, respectivamente. Problemáticas en cuanto al KDI fueron descubiertas durante el proceso de aplicación y comparación de estas metodologías y revelaron la necesidad de agregar indicadores adicionales, tales como Extracción de Mogotes y Karst Costal, así como otros perfeccionamientos adicionales y recomendaciones en cuanto a a escala, peso, y la incorporación de ambos métodos para crear uno sólo herramienta KDI que sea más práctica. La diseminación de los resultados de la evaluación del área utilizando el KDI educarán y ayudarán a promover la administración responsable y cuidado de este recurso vital de Puerto Rico.

Chapter One

Introduction

Karst environments are fragile landscapes, frequently containing non-renewable resources that have scientific, biological, cultural, mineralogical, recreational, hydrological, and economic importance (van Beynen and Townsend 2005; North 2007). Groundwater found in karst aquifers supplies over 25% of Earth's drinking water (Ford and Williams 2007). Karst landscapes have the unique characteristic of rapid subsurface drainage, which often presents myriad environmental problems, including surface collapse, flooding, drought, and desertification (Palmer 2007). Additionally, karst landscapes are progressively disturbed by economic, physical, and social processes. These disturbances include groundwater pollution, agricultural practices, urban development, cave modification, quarrying, and deforestation, among others (North 2007). The island of Puerto Rico is a fragile karst landscape due to its isolated geographic nature, wherein resources like karst aquifer-derived groundwater are limited; thus, the landscape is highly susceptible to increased water withdrawal and pollution, due in part to the restricted geographical boundary (Troester and White 1986).

In 2001, the United States Congress acknowledged Puerto Rico's karst environment as containing critical hydrological, ecological, and geological resources that are being threatened by development and other sources of anthropogenic disturbances. This is partly due to Puerto Rico having one of the highest population densities of any area of the United States (H.R. 3213). However, to effectively assess threats and disturbances to a karst environment, a holistic approach is needed to understand economic, scientific, and cultural factors contributing to the problem. Until the creation of a karst disturbance index (KDI) in recent publication by van Beynen and Townsend (2005), no such method of comparing, measuring, and contrasting the status of anthropogenic karst disturbance in a hierarchal and standardized fashion.

The KDI has already been applied in karst areas, specifically Italy and the Tampa Bay Metropolitan Area in Florida (van Beynen et al. 2006; North et al. 2008; de Waele 2009), and is currently being applied in Belize. The purpose of this research is to compare current KDI methodologies and create a holistic score for Arecibo, Puerto Rico, an area composed of the densely populated, urbanized extent in the Northern region with that of the more pristine, rural areas found within the Southern region of the municipality. The novelty of this study arises from examining two methodologies developed for the KDI: the original KDI developed by van Beynen and Townsend (2005), and the slightly modified version developed by De Waele (2009) that assesses disturbances rather than specific indicators. The original purpose of the KDI is to be used as a tool by non-experts in karst using available and easily obtainable data to assess the disturbance level of a karst terrain. Additionally, the results from the KDI is designed to be utilized for comparison between similar areas to aid in the determination of what is causing the score to differ or be the same so that potential problems can be addressed. Moreover, discourse about karst and environmental concerns, coupled with public education, can result from the dissemination of the KDI's findings. The aforementioned methodologies are employed and assessed to determine which methodology measures anthropogenic impacts more easily and accurately. In Puerto Rico, protecting the karst terrain and developing an index to assess the problem of karst disturbance is imperative due to the area's ever-growing population and its demands on the environment.

Research Strategy

Problem Statement

Fresh water resources are vital for human survival and are defined by Gleick (1993) as " …a fundamental resource, integral to all ecological and societal activities, including food and energy production, transportation, waste disposal, industrial development, and human health"(p.79). Fresh water comprises only 3% of the Earth's water resources. Of that, only 0.3% is in the form of surface water of lakes, swamps, streams, etc. The bulk (30.1%) of the accessible fresh water resources is stored as groundwater (USGS 1996). Karst regions are subject to more extreme anthropogenic impacts on water resources due to a lack of filtration mechanisms and direct inputs from the surface to the subsurface. Fragile ecosystems within caves can also be easily disturbed, where biota can be severely impacted. Additionally, caves are important for scientific research because they can provide data to past climates, have artifacts that have important archeological and anthropological significance, and they can provide information about geology and geomorphology of the area. The karst disturbance index (KDI) is a holistic tool that can be utilized to identify and characterize anthropogenic impacts affecting karst systems, which can subsequently impact groundwater resources and other important resources (van Beynen and Townsend 2005). The KDI has been implemented in only a few karst systems, revealing a variety of different impacts that affect karst environments in similar ways (Calo and Parise 2006; North et al. 2008). More implementation of the KDI is needed to aid in understanding the multitude of anthropogenic impacts on karst in other regions, as well as possible refinement of the Index's indicators (North et al. 2008).

Research Purpose

The purpose of this research is to measure anthropogenic disturbance to karst environments in Puerto Rico using the two current methods for the KDI to gain a more holistic understanding of impacts on Puerto Rico's island karst. In addition, an evaluation and further refinement of the original method was determined and a comparison of the two current methodologies was conducted that aims to assess which method is more accurate and efficient in measuring overall anthropogenic impacts to the study area. Also, to improve the practical application of KDI for parties outside of academe, interviews were conducted of government officials, community planners, and natural resource managers. Puerto Rico is an understudied karst area where the KDI has not been implemented but could help to understand the anthropogenic impacts on the karst environment.

Research Questions

- What are the anthropogenic impacts on karst in Puerto Rico?
- How can the KDI be utilized in this particular karst region and what changes/refinements will be needed and/or added to optimize the original index?
- Which KDI method will yield better results, and/or be more easily assessed?
- How will the severity of the impacts be shown through the results of the KDI methods and why?
- What is the perception of the KDI's usefulness as a tool?

Research Objectives

To answer the aforementioned research questions, the research objectives included:

- To apply the KDI to evaluate anthropogenic impacts on Arecibo, Puerto Rico's karst terrain.
- To determine the KDI's usability within the study area and ascertain changes /refinements that could be needed and/or added to the KDI through analysis of two current methods.
- To evaluate the results from the two methods and compare their ease of assessment or lack thereof.
- To analyze the results of the application of the two KDI methods to better understand how the methods' outcomes differ and determent the potential rational of the severity differences.
- To locate individuals with specific criteria and conduct interviews to determine their perception of the tool.

Literature Review

The origin of the name karst comes from the Kras Plateau region in Slovenia (Gams 1993). The study of karst began in the early 19th century. Jovan Cvijìc greatly advanced the discipline of karst geomorphology with his 1893 *Das Karstphänomen*, which had publication delays until 1960. W.M. Davis' role was minor until 1930, when he also advanced the field through new research (White 2007). More recent decades boast an evolution and specialization of the field that have drastically transformed the discipline of karstology from what it was 50 years ago. The multidisciplinary nature of karst research gives rise to new ways of understanding and exploring karst features (Ford 2006). Karst terrains are now recognized by the significant role they play in our environment because of their importance to water resources and ecosystems (Doerfliger 1999).

Karst can be defined as a type of terrain where unique geomorphologic landforms and hydrologic characteristics are created by the dissolution of bedrock. These landscapes result from the combination of high rock solubility, high secondary porosity, and chemical weathering properties indicative of carbonate lithologies. Karst features can take the form of caves, sinking streams, sinkholes, mogotes, cenotes, and closed depressions, among others (Ford 2002; Ford and Williams 2007). Carbonate rocks are primarily composed of calcium carbonate ($CaCO_3$), which forms from a variety of processes. These processes include, but are not limited to, calcite precipitation that takes places in shallow marine environments from various biota, such as fragments of seashells and coral. Ooids are also aggregated to the mix of biotic fragments and cemented together by a calcium matrix. Ooids and their larger counterpart Pisoliths are round balls formed by rolling waves and are composed of concentric layers of calcium carbonate (Palmer 2007). Limestone is the most common rock type in which karst landscapes form. The process of chemical weathering creates karst topographies and is caused predominantly by carbonic acid ($CO_2 + H_2O \rightleftharpoons H_2CO_3$). Carbonic acid is formed when carbon dioxide and water combine in the atmosphere and biosphere (mainly the soil), thus becoming slightly acidic and capable of dissolving limestone and similar carbonate rock types such as, dolomite and marble.

Over the course of geologic time, this process creates karst features that are critically important to human water resources due to their interconnected and dependent relationship with each other, including conduit and cave passages, and aquifers. Another key component to the formation of karst landscapes is strata orientation (dip), number of fractures, and overlying rock types. These properties help form specific features, such as caves, and determine various characteristics of karst attributes (Beck 1978, Ford 2002). Climate plays a significant part in the formation of different karst regions because of the aforementioned processes; for example, the more annual rainfall a karst region receives the higher the potential for chemical weathering processes to occur along fractures and weak bedding planes. Moreover, a tropical climate has dense vegetation and forms thick, carbon dioxide rich soils. However, other factors also include temperature, rock competency, chemical constituents/gases (i.e. sulfur), pH (disambiguation), dissolved solids (i.e. sodium chloride) and soil overburden (Palmer 2003; Ford and Williams 2007).

Anthropogenic Impacts to Karst

Climate change at any scale, whether manmade or natural, can affect a karst environment. Micro-scale changes, like cave entrance alteration for tourist caves or infilling of sinkholes, are potential anthropogenic impacts to cave climate and biota. Meso-scale changes, such as localized deforestation, and macro-scale changes to global climate could affect components of a karst landscape. Examples of this include precipitation/evaporation changes or the intrusion of saltwater in freshwater aquifers due to rising ocean levels. Many anthropogenic activities are deleterious to the hydrology and ecology within a karst landscape. Measuring these impacts is a challenge because of the various scales and ways by which they are manifested in different karst regions.

Infrastructural Impacts

Anthropogenic alteration of karst landscapes has significant impacts. Clear cutting of forests and deforestation causes impacts to biota and surface soils that influence the way in which water moves into a karst system, and also affects the geochemistry and natural filtration properties of karst systems. Agriculture, like clear cutting, promotes the same anthropogenic impacts, but also includes more severe repercussions with the influx of pesticides and other harmful chemicals (Zimmerman et al. 2000; Chinea and Helmer 2002; Holechek et al. 2003). Dams create yet another negative quandary to hydrologic issues in karst regions by affecting the flux of water in and out of the system.

Pollution Impacts

Pollution, such as landfill seepage, infilling of sinkholes, sewage, oil spills, and all other components of human waste, inevitability find their way into the groundwater if mitigation measures are not in place. These factors are perhaps the most hazardous in karst regions because of how karst functions to pirate water into the subsurface without strong soil and rock filtration mechanisms. Urbanization in or near karst areas causes even more problems, with runoff of pollutants from streets and businesses, such as, BTEX (benzene, toluene, ethylbenzene, and xylenes) chemicals, further polluting the groundwater and affecting aquifer development (Ryan and Meiman 1996; Keller 2000; White 2007).

Evaluation of Karst Disturbances

Karst is a dynamic and complex system relied heavily upon by ecosystems and people for resources, such as groundwater. The need to protect this vital resource is paramount. Human induced and environmental factors need to be measured and addressed on an individualized and need-basis (Lugo et al. 2001; van Beynen and Townsend 2005; North 2008). Anthropogenic factors encompass a wide range of components and are comprised of many interconnections. When dealing with karst environments, it is of great importance to understand the regions in which karst systems are located because of their heterogeneous nature. There are many tools available, such as Geographic Information Systems (GIS), geochemistry, and remote sensing that help in the understanding of karst features and the impacts on the environment, some of which can be utilized for measuring important factors and various characteristics that can be integrated into the karst disturbance index.

The KDI is a way in which policymakers, planners, and other interested parties can try to understand all relevant anthropogenic factors in a standardized model. This tool can then be used to disseminate findings to educate people, hopefully bringing about stewardship and legislation to foster protection and mitigation of impacts. However, the index may need further refinement as to incorporate important characteristics within existing indicators and/or have new indicators added that address specific issues concerning the study area. The KDI should be applied to more karst systems to catalog them for better understanding and identifying possible issues with the methodology and comparative analysis between locations. Our understanding of karst systems has grown greatly since man's first venture into caves during prehistoric times; however, there is still a need to understand these systems further so as to better protect the valuable resources within karst landscapes. The island of Puerto Rico is a unique landscape with an isolated geography where resources like groundwater are limited, and highly susceptible to increasing development and pollution (Troester and White 1986).

Chapter Two

Study Area

This research was conducted in a primary karst region in the municipality of Arecibo (Figure 1). Arecibo is located in the Northern Midwest coast of Puerto Rico bordering the Atlantic Ocean. This study area was chosen to represent both an area that is fairly pristine with minimal urbanization (southern half) and an area that is heavily populated and urbanized (northern half) (Lugo et al. 2001).

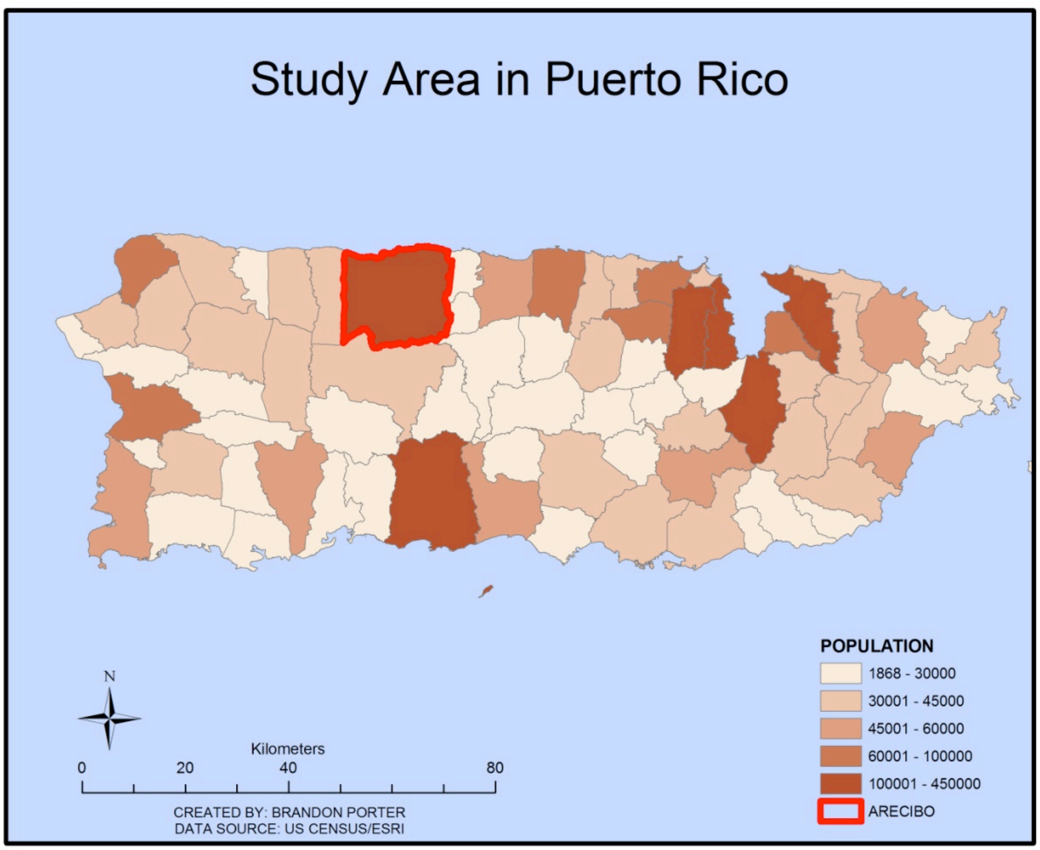

Fig. 1 Map of Study Area (U.S. Census Bureau 2008(a), ESRI 2008)

Puerto Rico Geography and Climate

Puerto Rico is the smallest and most eastern island in the Greater Antilles. The coast's accumulated length is approximately 580 km. Several islands are also a part of the Puerto Rican Commonwealth and include: Culebra, Culebrita, Mona, Monito, Palomino, Vieques, and smaller isolated islands. The Puerto Rico Trench lies off the northern coast at a depth of more than 28,000 feet (8,500 meters). The Venezuelan Basin of the Caribbean lies off the southern coast and is 16,400 feet (5,000 meters) deep. There are 78 municipalities that divide the commonwealth politically (Boose et al. 2004). Puerto Rico was subdivided into 11 geographic regions by Pico (1950). These regions consisted of the Northern Coastal Plain, Humid Valleys of the East Coast, Caguas Valley, South Coastal Plain, Semiarid Southern Foothills, Humid Northern Foothills, Humid Mountains of the East, Rainy Mountains of the West, Sirra de Luquillo and the islands of Vieques, Culebra, and Mona (Lugo et al. 2001). Monroe proposed three physiographic regions in 1976: the karst belt, the mountainous area, and the discontinuous coastal plains (Lugo et al. 2001). There are three regions of limestone on the island: Northern limestone, Southern limestone and dispersed limestone. The Northern limestone region is located along the north coast and contains a well-defined aquifer. The Southern limestone region lies along the south coast and the dispersed limestone consists mostly of all the limestone lenses on the interior of the island (Lugo et al. 2001).

The climate of Puerto Rico is tropical marine with an average temperature of 80°F (26°C). Prevailing wind direction is caused by the easterly trade winds. Rainfall amounts double during May to October and are mostly evenly distributed throughout the rest of the year. The precipitation on the north coast is roughly double that of the south coast, partially due to the rain shadow effect. Precipitation annually varies by region: the north receives approximately 1,550 mm (61.02 inches), the south receives approximately 910 mm (36 inches), the coastal regions and the mountains receive 101-381 cm (40-150 inches) and 508 cm (200 inches) respectively (Boose et al. 2004). The island of Puerto Rico is exposed to many cyclones of the Caribbean. Hurricane season for the North Atlantic Basin starts on June 1 and ends on November 30 (NOAA 2010). Hurricane seasons during 1995-2004 have averaged 13.6 tropical storms (34-63 knots), 7.8 hurricanes (>63 knots) and 3.8 major hurricanes (>95 knots) (NOAA 2010(a); topuertorico.org).

Puerto Rico Geology and Geomorphology

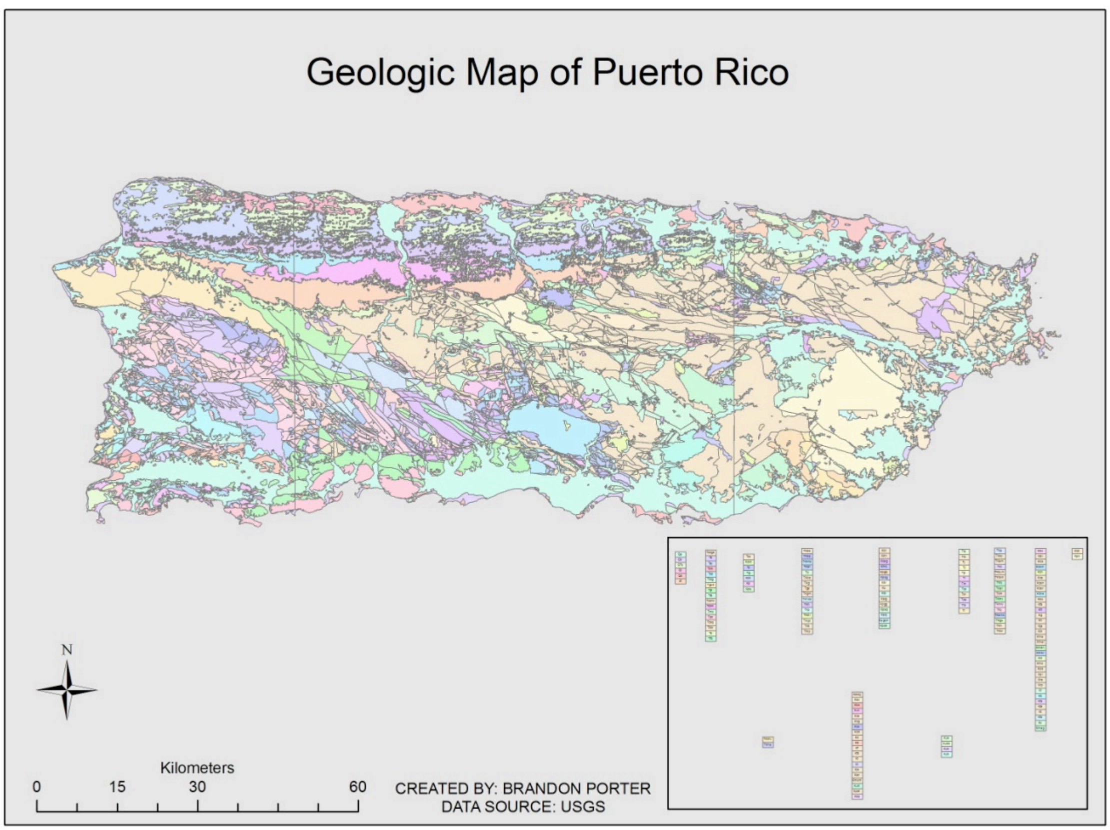

Fig. 2 Map of Geologic Formations (USGS 2010)

The limestones of the Northern karst belt lie unconformably on a volcanic basement due to faults and folds (Giusti 1978). The ages of the limestone ranges are estimated to be from middle Oligocene to middle Miocene (Giusti 1978). Six formations are the principal formations (descriptions are loosely taken from Giusti 1978 and a 1968 USGS geologic map of the Arecibo quadrangle):

San Sebastián Formation

This formation is a poorly cemented shaly bedded claystone. It contains layers of siltstone, conglomerate, sandstone, and has lenses of limestone and lignite. The thickness of this formation is between zero and 300 m. The age is controversial but agreed to be middle Oligocene. The San Sebastián is a mostly impermeable stratum that acts as a confining bed for most of the area.

Lares Limestone

This formation overlies the San Sebastián and is limestone with thin and thick bedding. The center of the belt is about 300m thick and thins East to West pinching out at the belt margins. The age is controversial also, but most consider it to be of middle and late Oligocene age. This formation has low permeability and makes for a poor aquifer except at the belt’s center where the high potentiometric head causes it to become an aquifer.

Cibao Formation

The Cibao has two recognized members: the Montebello Limestone Member and the Quebrada Arenas Member. This formation has interbedded sequences of limestone, marl, chalk, sand, and clay as thick as 230m. This formation is a confining bed or an aquifer depending on the lithology. The Quebrada Arenas and Montebello Limestone members are crystalline to granular limestones that are thick-bedded to massive located in the middle of the belt. The Cibao Formation ranges from Oligocene to Miocene in age or is entirely Miocene.

Aguada Limestone

This unit consists of calcarenite that is thick-bedded to massive with alternating beds of clayey limestone. The thickness does not exceed approximately 90m and is early Miocene in age. The ability to hold water for this limestone is poor to fair.

Aymamón Limestone

The Aymamón base is a massive to thick-bedded limestone that is finely crystalline with a thickness of about 70m and has a poor to fair ability to hold water. The remainder of the limestone is very pure chalky limestone that is highly permeable and has many solution conduits. All together the maximum thickness is approximately 300m and is early Miocene in age.

Camuy Formation

The lithology of the Camuy formation varies from a calcarenite to a limestone conglomerate in a clayey matrix with some parts composed of quartz sandstone. The unit is no more than 200m thick and is Miocene to Pliocene in age, the latter is based on some micropaleontological work. This formation is above the water table and thus is not an aquifer.

Puerto Rico Karst

The karst terrain of Puerto Rico is diverse and has both holokarst, with complete karstic drainage, and fluviokarst, a mixture between karst landforms and fluvial characteristics (White 1988; Lugo et al. 2001). The lithology undergoes different erosion rates and the dip is mostly between 1 and 5 degrees (Lugo et al. 2001). Many geomorphic landforms are found in Puerto Rico karst and include but not limited to: caves, sinkholes, mogotes, cockpits, dry valleys, subterranean rivers, cuesta karst, broad valleys, zanjones and karren (Lugo et al. 2001). The most notable karst region is the northern karst belt which encompasses the study area. The limestones that give rise to aforementioned features are vast and cover an area approximately 125 kilometers in length from west to east and are as wide as approximately 22 kilometers near Arecibo and covering about one-fifth of the island's area (Giusti 1978). The vertical range of this belt is anywhere between a few meters near the coast to 400 meters inland.

Arecibo, Puerto Rico

Arecibo is the name of both the city and the municipality. The Río Grande de Arecibo and Río Tanamá are the two rivers that flow through the city. Annual precipitation is approximately 53 inches and has an average temperature of approximately 78 degrees Fahrenheit. The land area of the municipality is approximately 330 sq km (127 sq mi). Population is estimated at 102,770 in 2009 U.S. census and has a per capita income of $7,290. Arecibo companies produce rum, agricultural machinery, clothing, paper, plastics, and sporting goods, all of which use valuable resources and produce significant waste (Encyclopedia Britannica 2010; topuertorico.org).

The municipality of Arecibo lies within the northern karst belt where the geology is primarily comprised of limestones (Figure 3). Karst features include but are not limited to: caves, mogotes, sinkholes, subterranean river, and broad valleys. Cueva de la Ventana and Cueva de los Indios are two well-known tourist caves in Arecibo. The world's largest radio telescope, the Observatorio de Arecibo, is also located here, due in part to the existence of a large sinkhole that was able to house the dish.

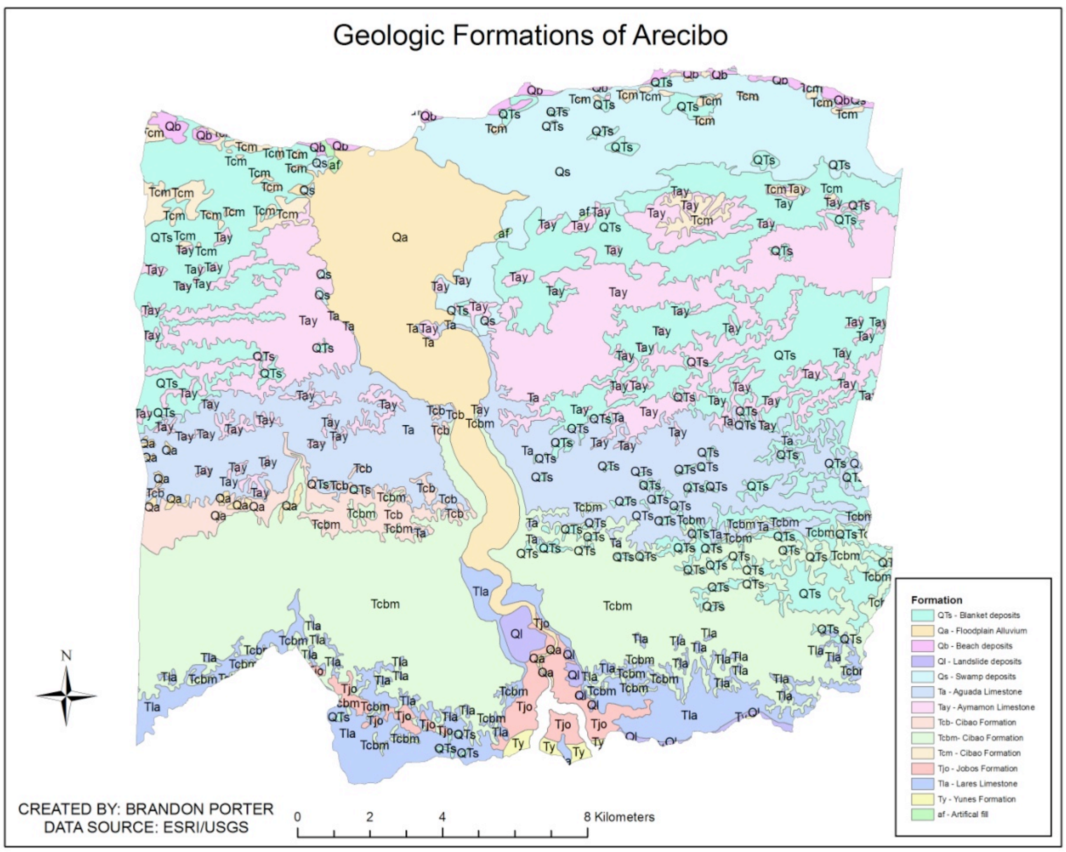

Fig. 3 Map of Geologic Formations in Arecibo (USGS 2010)

The municipality of Arecibo has coastal wetlands named Caño Tiburones, which are located in the northeast along the coast. The Cambalache Forest Reserve is located in Arecibo and contains plantations of eucalyptus, teak, and mahoe trees (topuertorico.org).

Nearly half of the area is covered by dense vegetation, however, through remotely sensed images many natural and manmade features can be seen (such as, mogotes, rivers, and various infrastructures, including the Dos Bocas hydroelectric dam and reservoir in the south) (Figure 4).

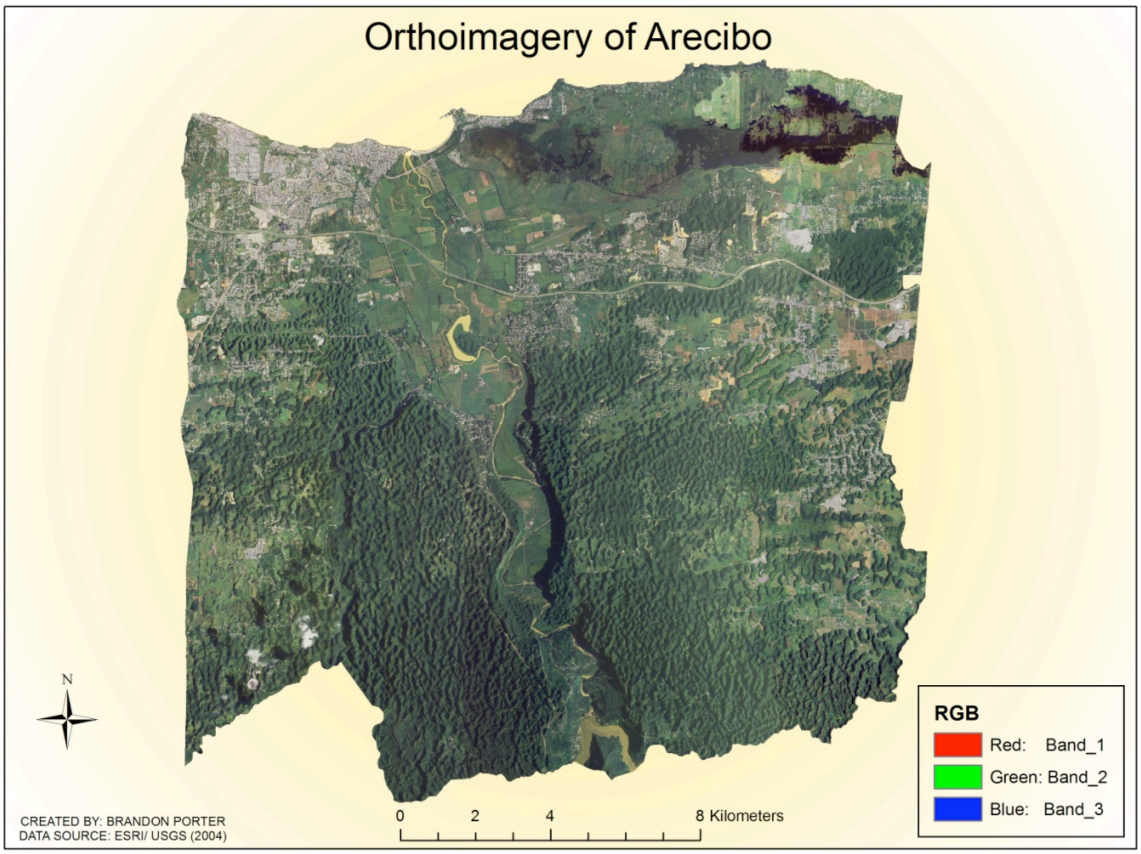

Fig. 4 Orthoimagery Map of Arecibo (USGS 2004)

Chapter Three

Methodologies

For this study, two different variations of the KDI were used and compared to illustrate strengths and weaknesses of the similar methods for the purpose of identifying a better way to measure and analyze anthropogenic impacts on karst.

Summary of Methodologies

Original Method

The figure below (Figure 5) is a flowchart that outlines the original methodology.

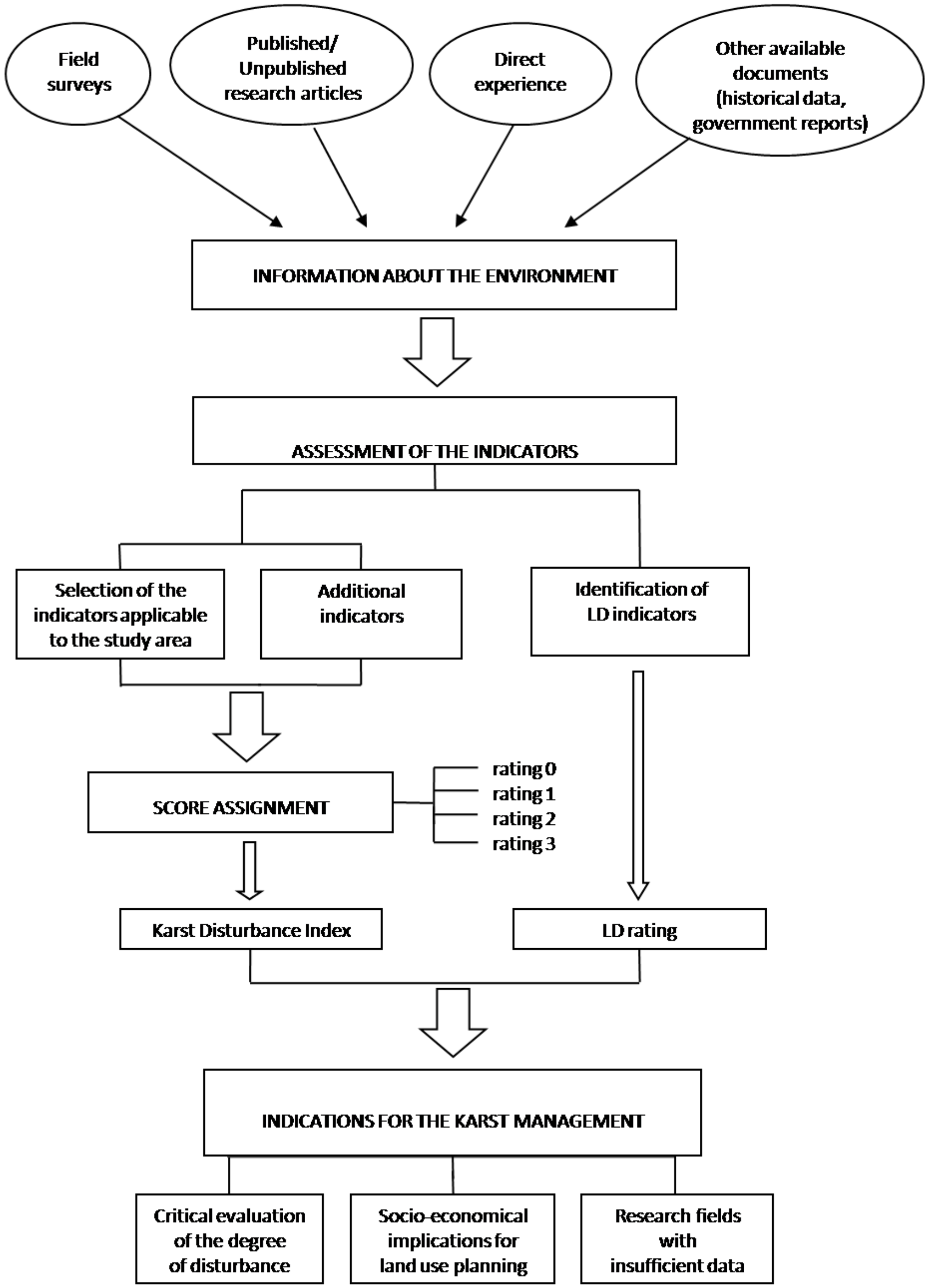

Fig. 5 Flow Chart Summarizing Original KDI Study Methodology. From Caló and Parise 2006.

Modified Method

The figure below (Figure 6) is a flowchart that outlines the modified methodology.

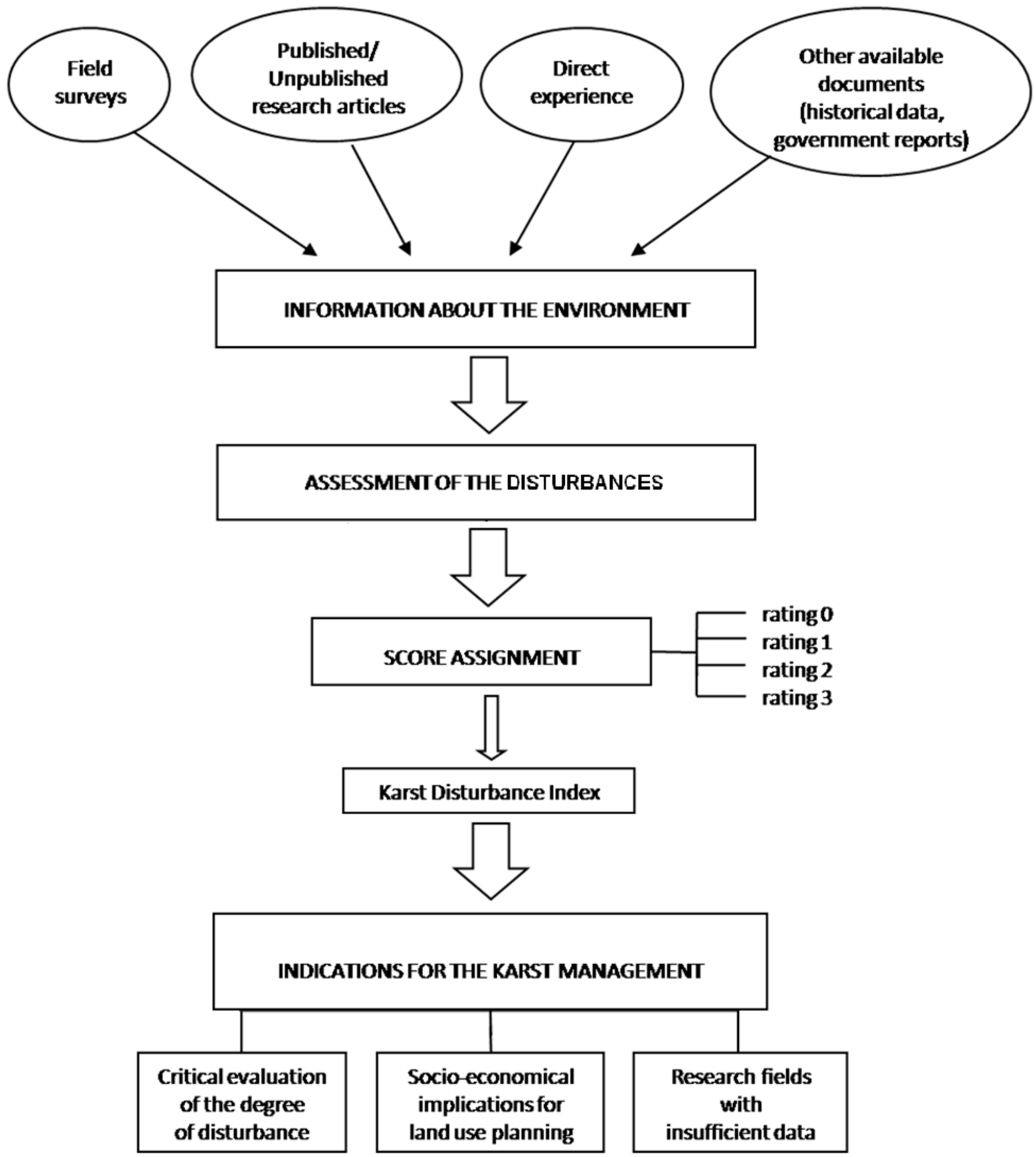

Fig. 6 Flow Chart Summarizing Modified KDI Study Methodology. Modified from Caló and Parise 2006.

Description of Indicators Used for Original Methodology

Data collection for this methodology includes both primary and secondary data sources, such as GIS shapefiles, government reports, United States Geological Survey (USGS) topographic maps and hydrologic data, combined with field work to groundtruth sinkhole, cave, and spring data for the corresponding KDI indicators and discovery of the need for any new indicators (*Table 1*). Data was also gathered from environmental experts in the region. Fieldwork in January 2010 included both physical collections of data (i.e. cave location points, cave surveying, groundwater monitoring, sinkhole groundtruthing and infilling verification, on-site map and historical document research, etc.). Once collected, the KDI indicator data for Arecibo was analyzed to determine the KDI scores and primary disturbance indicators.

Table 1 Data sources used to score the disturbance indicators in Arecibo, Puerto Rico

Indicator	Data source
Quarrying/mining	USGS topographic maps/GIS/fieldwork
Flooding (due to human-built structures)	USGS, NOAA, Municipality resources
Stormwater drainage	UPRM Stormwater Management Program
Infilling	USGS topographic maps/fieldwork
Dumping	EPA Cleanup Sites
Compaction	Puerto Rico GIS Data
Pesticides and herbicides	Puerto Rico Dept. de Agiculturo
Industrail and petroluem spills or dumping	Puerto Rico EPA
Concentrations of harmful chemical constituents in springs	Field work, Puerto Rico EPA
Changes in the water table	USGS
Vegetation removal	Land use/Land cover, Canopy Cover Raster
Groundwater biota – species richness	Fieldwork
Groundwater biota – population density	Fieldwork
Destruction/removal of historical artifacts	Fieldwork; local historical records
Regulatory protection	Puerto Rico Statutes; local regulations
Enforcement of regulations	Puerto Rico DEP
Public education	EPA website, Puerto Rico Water and Environmental Association website
Building over karst features	Aricebo GIS data/fieldwork
Building of roads	Aricebo GIS data/fieldwork

Scoring System

Each indicator was assigned a score according to the compilation of the KDI indicators (*Table 1*) from van Beynen and Townsend (2005). The scores ranged from 0 to 3; with 0 indicating no human impacts, 1 indicating localized and not severe, and 2 indicating severe disturbance. Additionally, a disturbance scale was assigned for each indicator: macro- to indicate a large scale disturbance, meso- to indicate a localized small scale disturbance, and micro- to indicate a highly concentrated small scale disturbance. The sum of all indicator scores were then divided by the highest possible score. The resulting number ranged from 0 to 1. This figure indicated a karst disturbance level category, as defined by van Beynen and Townsend (2005) and modified by North (2007): 0.0-0.19 (pristine), 0.2-0.39 (minor disturbance), 0.4-0.5 (moderate disturbance), 0.51-0.6 (significantly disturbed), 0.61-0.7 (severely disturbed), 0.71-0.8 (critically disturbed) and 0.81-1.0 (irreversibly disturbed). The higher the figure, that is closest to a value of 1, the greater the degree of disturbance identified.

Level of Confidence

A Lack of Data (LD) score was used to designate indicators that, while applicable to the study area, did not have adequate or sufficient data, as indicated by KDI guidelines. The degree of confidence in the calculated disturbance level of the municipality is represented by a total LD score from 0 to 1, which is obtained by dividing the total number indicators assigned an LD scored by the total number of applicable indicators. Inapplicable indicators were completely disregarded (van Beynen and Townsend 2005). High confidence in the index results would be represented by a total LD score less than

0.1, while a total LD score of more than 0.4 would indicate that the findings are insufficient and more research should be conducted. Higher LD scores indicate higher degrees of uncertainty in regards to the calculated degree of disturbance to the area. Table 2, taken from van Beynen and Townsend (2005), shows how each indicator might be assessed and provides a general guideline.

Assessment of Indicators

The indicators (Figure *7*), and how they were evaluated in this study is addressed in detail below. Caves and sinkholes were found through secondary sources; GIS shapefiles, local caving experts, park officials, and publications that pertain to karst formations within the study areas.

Category	Attribute	Scale	Indicator	3	2	1	0
Geomorphology	Surface Landforms	Macro	Quarrying/ Mining	Large open cast mines	Small working mines	Small scale removal of pavement	None
		Macro /Meso	Flooding (human built surface structure)	Total flooding of valley for hydroelectric dams	Flooding of fields for irrigation	Small scale reservoirs built for farming	Natural precipitation induced flooding
		Meso	Stormwater drainage (% of total stormwater funneled into sinks)	>66%	34-66%	1-34%	None
		Meso	Infilling (% of infilled caves/sinks)	>66%	34-66%	1-34%	None
		Micro	Dumping (% of sinkholes affected)	>66%	34-66%	1-34%	None
	Soils	Macro	Erosion	Severe	High	Moderate	Natural rate
		Micro	Compaction due to livestock or humans	Widespread and high levels	Widespread but low levels	Few isolated concentrated areas	None
	Subsurface Karst	Macro	Flooding (human-induced flooding due to surface alteration)	Permanent cave inundation	Increased intermittent flooding & >50% filling	Increased intermittent flooding & <50% filling	Only natural flooding due to high rainfall
		Micro	Decoration removal – vandalism	Widespread destruction	~50% of speleothems removed	Isolated spots of removal	Pristine

Fig. 7 Karst Disturbance Indicators. (Taken from van Beynen and Townsend 2005, p. 106).

Geomorphology (continued)	Subsurface Karst (continued)	Micro	Mineral – sediment removal	Most of Material removed	~50% of cave affected	Some isolated spots
		Micro	Floor sediment compaction – destruction	Most of floor sediments – decorations affected	~ 50% of floor sediments – decorations affected	Small trail through cave
Atmosphere	Air Quality	Macro	Desiccation	Widespread and high levels	Widespread but low levels	Isolated and very low levels
		Micro	Human- induced condensation corrosion	Widespread and high levels	Widespread but low levels	Isolated and very low level
Hydrology	Water Quality – Surface Practices	Meso	Pesticides and herbicides	Leakage of concentrated chemicals into aquifer	Heavy spraying of crops/weeds on surface	Little use of chemicals
		Micro	Industrial/ petroleum spills or dumping	>20 Brownfields	10-19 Brownfields	1-9 Brownfields
	Water Quality – Springs	At all Scales	Concentrations of harmful chemical constituents in springs	Harmful year round	Harmful for short periods	Just above natural levels
	Water Quantity	Macro	Changes in water table (decline in meters)	>35	15	<5

Fig. 7 (Continued)

Hydrology (continued)	Water Quantity (continued)	Micro	Changes in cave drip waters	Total cessation	Long dry spells (not seasonal)	Slight reduction
Biota	Vegetation Disturbance	At all scales	Vegetation removal (% of total)	>66%	34-66%	1-34%
	Subsurface Biota – Cave	Micro	Species richness (% decline)	50-75%	20-49%	1-19%
		Micro	Population density	50-75%	20-49%	1-19%
	Subsurface – Groundwater	Micro	Species richness (% decline)	50-75%	20-49%	1-19%
		Micro	Population density	50-75%	20-49%	1-19%
Cultural	Human Artifacts	At all scales	Destruction/ removal of historical artifact (% taken)	>50%	20-49%	1-19%
	Stewardship of Karst Region	At all scales	Regulatory protection	No regulation	A few weak regulations	Statutes in place but with loopholes
		At all scales	Enforcement of regulations	Widespread destruction/no enforcement	No policing but little damage done	Some infrequent enforcement
		At all scales	Public Education	None, public hostility	None, public indifference	Attempts through NGOs
	Building infrastructure	Macro	Building of roads	Major highways	Some two lane roads	Some country lanes
		Meso	Building over karst features	Large cities	Some two lane roads	Some country lanes
		Micro	Construction in caves	Major modification	Major tourist cave	Cave trail marked

Fig. 7 (Continued)

Scoring of Indicators for Original Methodology

Geomorphology – Surface landforms

Several primary and secondary data sources were utilized to assess the degree of disturbance for each indicator. Quarrying and mining sites were derived from USGS topographic maps to determine the prevalence and specific numbers in each municipality. Additionally, officials provided confirmation of these sites and those that were not available from the topographic maps. Remote sensing was utilized to determine and provide a measure of confirmation through visual inspection.

Flooding due to human built structures was assessed through USGS flood and stream data. Municipality resources pertaining to urbanization and sprawl were employed to ascertain the degree of change in infrastructure and how this impacts flooding in denoted areas. A compilation of GIS (spatial analysis) coupled with remote sensing was utilized to show land use/land cover change over the study area to extrapolate changes in the aforementioned infrastructure. In addition, inquiries to relevant parties were made about flooding issues that have been witnessed after a structural change.

Infilling and trashing of sinkholes were assessed using USGS topographic maps, aerial photos, and pre-existing data. Sinkhole infilling can be determined by comparing sinkholes in older topographic maps with that of current maps to extrapolate the percent loss of sinkholes before and during periods of rapid urbanization. Published research discussing the percentage loss of sinkholes was also utilized. In situ data collection through randomized sampling was used to confirm the topographic map, aerial photo, and secondary data. In addition, land use/land cover changes show where urbanization occurred and can also be used to determine potential loss of sinkholes. Dumping of garbage and other containments were assessed through visual inspection of visited sinkholes.

Geomorphology – Soils

Soil erosion and compaction from anthropogenic practices were assessed using land use/land cover data. Through analysis of this data set determining where soil erosion occurs due to deforestation was possible. Soil compaction was determined by urban infrastructure that creates impervious surfaces along with agriculture where cattle compact soil.

Geomorphology – Subsurface Karst and Atmosphere – Air Quality

Assessing a score for the use of pesticides and herbicides involved the analysis of the frequency and quantity of herbicide and pesticide application within the study area. This was done through evaluation of policies pertaining to the regulation and application of pesticides and herbicides, as well as any local groundwater monitoring data. In addition, personal interviews with officials from the municipalities provided additional information of the level of pesticide and herbicide application in each study area regarding the number of establishments regularly applying these chemicals.

GIS shapefiles from the United States Environmental Protection Agency (EPA) website were used to determine the number of superfund, brownfields, and other hazardous waste sites present in each municipality to evaluate the point sources of industrial and petroleum spills or dumping indicators (Figure 21). In addition, any information contained within the literature pertaining to groundwater contamination was utilized. Concentrations of harmful chemical constituents in springs were assessed through fieldwork, water quality data, and related data derived from the Puerto Rico Department of Natural Resources. Changes in the water table were assessed through USGS potentiometric surface maps and other relevant groundwater data.

Hydrology – Water Quality

Harmful chemical constituents are found in springs and wells throughout the study area and were assessed through secondary data sources such as USGS and EPA. Many sources of contamination were from industrial spills (superfund sites), toxic release sites, and hazardous waste sites. Surface practices from pesticide and herbicide use and illegal dumping of refuse also greatly impacted the water quality indicators and the data was utilized for assessment. Other relevant data sources such as Leaking Underground Storage Tanks (LUST) lists were obtained and aided in determining a score for the *leakage from underground tanks* indicator.

Biota – Vegetation Disturbance and Subsurface Species

Vegetation removal and subsequent soil erosion from clear cutting was determined through remote sensing. Canopy cover and land use/ land cover data was obtained of the study area. This enabled extrapolation of areas and extents of vegetation removal though analysis, and provided a calculation of the total percentage of deforestation in each municipality to evaluate the *vegetation removal* indicator.

Cultural – Human Artifacts

Destruction, vandalism, and removal of historical artifacts were assessed utilizing local historical records and fieldwork. Personal assessment of the degree of vandalism and destruction took place in caves visited. Speleothem removal, percentage of area within the caves affected by sediment removal, level of construction within caves, desiccation, human-induced condensation corrosion, and the percentage of cave floor affected by soil compaction was assessed similarly to ascertain the level of disturbances for these indicators. The percentage of each disturbance was calculated by dividing the number of caves that fit the disturbance indicator being analyzed by the total number of caves – with the exception of vandalism, which was calculated by dividing the number of formations remaining by the number that should be present in the cave. Personal interviews with local caving experts provided information of the changes of cave drip waters and water flow within caves in the study area.

Cultural – Stewardship of Karst

The determination of administrative codes, government statutes, and programs relating to the protection of karst through internet searches and personal interviews was used to evaluate the *regulatory protection* indicator, and the accessibility of these regulations and programs to the public. Local, municipal, and government websites and personal interviews with officials from the municipality were used for the *public education* indicator, due to the nature of public education being largely internet-based or clearly stated on government websites.

Cultural – Building of Infrastructure

U.S. Census Bureau reports provide information on the degree of road building and other infrastructure occurring on karst features through GIS shapefiles and reports. In addition, a comparative analysis of maps from different decades was used to show the evolution of road infrastructure. Moreover, remote sensing again was used to extrapolate and evaluate *the building of roads* indicator through analysis of land use/land cover.

Participant Interviews/Surveys

The following questions were asked in order to attain information on how the KDI is used as a tool, and how the participants perceived the method used to gather data and its overall usefulness to them. These interviews were conducted through a semi structured; face to face format of individuals who incorporated karst in their work. Moreover, the purpose of the interviews was to add to the findings by interviews conducted by North (2007). Additionally, the surveyed individuals provided feedback that was used to identify potential refinements along with recommendations to make the index a viable tool that will increase the likelihood of it being used outside of academics. The individuals for the conducted interviews and surveys were chosen to include the most likely candidates that would use the KDI in Puerto Rico and the study area and would benefit from its results. Moreover, dissemination of the findings is perhaps the most important aspect of the KDI so that parties with vested interests can include the data in their on-going efforts to protect the karst environment. Analysis of survey results is addressed within the discussion chapter.

Sample Interview Question Set

1) *In your work, do you incorporate knowledge of karst?*

2) *Do you have any training or education in karst science?*

3) *Is the Karst Disturbance Index useful to your work? Why or why not?*

4) *What do you think could be incorporated into the KDI to make it more useful?*

5) *How do you define and/or describe qualitative and quantitative data?*

6) *What sort of information is valuable to you? (Qualitative, Quantitative, both)?*

7) *How do you use qualitative data, do you use it with quantitative data?*

Sample Survey Question Set

Data for several indicators were needed to augment other data sources. Thus, experts from the study area were surveyed for the purpose of attaining the needed information. Experts included, but are not limited to, government officials, local non-government organizations (NGO's), cave surveyors, cave enthusiasts, and scientists who have performed various work in the caves over many years and are well acquainted with the caves in Arecibo.

Survey for Specific Karst Disturbance Index indicators for Arecibo, Puerto Rico

Please answer the following questions and provide any details applicable to support your assessment. Additionally, please include a timeline that includes when you first began any research or exploration in caves within the study area with as much detail as you possibly can (i.e. Cave names, research undertaken in said cave, cave type, location, *basic lithologies of the cave, etc). Your answers will greatly help in assessment of the KDI indicators for my thesis. Thank you very much in advance for taking the time.*

Geomorphology, Subsurface Karst: Decoration removal – vandalism

Overall, would you describe the caves conditions that you surveyed/explored/performed research in by one of the following conditions: Widespread destruction, approximately 50% of speleothems removed, isolated spots of removal or pristine?

Geomorphology, Subsurface Karst: Mineral – sediment removal

Overall, would you describe the caves conditions that you surveyed/explored/performed research in by one of the following conditions: Most of material removed, approximately 50% of cave affected, some isolated spots or none perceived?

Geomorphology, Subsurface Karst: Floor sediment compaction-destruction

Overall, would you describe the caves conditions that you surveyed/explored/performed research in by one of the following conditions: Most of floor sediments-decorations affected, approximately 50% of floor sediments-decorations affected, small trail through cave or pristine upon entering?

Atmosphere, Air Quality: Desiccation

Overall, would you describe the caves conditions that you surveyed/explored/performed research in by one of the following conditions: Widespread and high levels, widespread but low levels, isolated and very low levels or pristine upon entering?

Atmosphere, Air Quality: Human- induced condensation corrosion

Overall, would you describe the caves conditions that you surveyed/explored/performed research in by one of the following conditions: Widespread and high levels, widespread but low levels, isolated and very low levels or pristine upon entering?

Hydrology, Water Quantity: Changes in cave drip waters

Overall, would you describe the caves conditions that you surveyed/explored/performed research in by one of the following conditions: Total cessation, long dry spells (not seasonal), slight reduction or none perceived?

Assessment of Disturbances Utilizing Modified method

Data obtained for the original method were utilized for assessment of the modified method. Although the methods differ slightly, the data used in the original method was easily adjusted to identify individual disturbances and the assessments also translated over to a large degree. This was due to the fact that one or more individual disturbances comprised the assessment of the indicators. However, differences between the two approaches excluded the data from *regulatory protection, enforcement of regulations* and *public education* indicators from being utilized because they are not considered individual disturbances. Moreover, some fieldwork data not used in the original method were employed in the modified method, for example the 'Sewage' disturbance.

Scoring of disturbances mirrors the original method scoring system of indicators with the exception of the 'Lack of Data' designations (LD). The modified method excludes these designations, thus, eliminating the level of confidence score. The calculation of the total disturbance score is not changed and involves the division of the sum of all scores by the highest possible score. The resulting score between 0 and 1 is then assigned one of the seven karst disturbance level categories refined by North (2007) but based on van Beynen and Townsend (2005): 0.0-0.19 (pristine), 0.2-0.39 (minor disturbance), 0.4-0.5 (moderate disturbance), 0.51-0.6 (significantly disturbed), 0.61-0.7 (severely disturbed), 0.71-0.8 (critically disturbed) and 0.81-1.0 (irreversibly disturbed).

Due to the similarities of the methods the results are somewhat redundant with several exceptions. However, the exceptions provide valuable insight into how the KDI can be refined and how the modifications from the original method by de Waele (2009) impact the resulting KDI score.

Chapter Four

Results

Scoring of Indicators for Original Method

The application of the original method for the study area of Arecibo, Puerto Rico was performed from 2009 to 2010. The results are summarized in (Table 2) followed by a detailed description for the rationale of each assessment of the indicator scores for Arecibo, Puerto Rico.

Table 2 Summarized Results from Original Method

Category	Attribute	Scale	Indicator	Score	Justification
Geomorphology	Surface Landforms	Macro	Quarrying/Mining	3	There are three metal mines (gold, iron, and silica), 32 general limestone quarries, 5 stone and crushed/broken limestone quarries and 8 sand and gravel limestone quarries
		Macro /Meso	Flooding (human built surface structure)	3	The Dos Bocas hydroelectric dam and reservoir constructed in 1942 and is the second largest hydroelectric dam in Puerto Rico and spans 30,420 acre-feet. Additionally, the largest wetland the Cano Tiburones is irrigated for crops
		Meso	Stormwater drainage (% of total stormwater funneled into sinks)	LD	Insufficient data to confidently assess indictor
		Meso	Infilling (% of infilled caves/sinks)	LD	Insufficient data to confidently assess indictor
		Micro	Dumping (% of sinkholes affected)	1	Dumping found in sinkholes in close proximity to urban areas. Majority of sinkholes assumed to be pristine due to inaccessibility caused by dense mogotes (steep karst features) and vegetation.
	Soils	Macro	Erosion	2	Herbaceous land cover is approximately 23% and is assumed in this assessment to be land recovering from deforestation and other anthropogenic practices. Agriculture accounts for approximately 9% and developed land approximately 14%. Additionally, Study area is largely comprised of steep gradients
		Micro	Compaction due to livestock or humans	2	Agriculture accounts for about 9% and urbanization about 14% of the land use, covering 23% of the study area
	Subsurface Karst	Macro	Flooding (human-induced flooding due to surface alteration)	3	Dos Bocas hydroelectric dam and reservoir (30,420 acre-feet)
		Micro	Decoration removal – vandalism	2	Of the eleven known and documented caves, five had decoration removal, vandalism, or both accounting for approximately 45% of the caves

Table 2 Continued

Geomorphology (continued)	Subsurface Karst (continued)	Micro	Mineral – sediment removal	1	Guano removal was widespread and was mined in many caves. However, this practice was done in the past by locals
		Micro	Floor sediment compaction – destruction	1	Two tourist caves that are frequently visited and experience a high volume of foot traffic. Cueva de la Ventana has significant floor compaction and rock erosion caused by tourists in approximately 50% of the upper passage way
Atmosphere	Air Quality	Macro	Desiccation	1	Two tourist caves that receive high traffic with only one cave having speleothems (Cueva de la Ventana). Neither cave has lighting so the primary source for desiccation is body heat.
		Micro	Human- induced condensation corrosion	1	High levels of human-induced condensation corrosion is only prevalent in one cave. The majority of the caves in the study area have very little traffic
Hydrology	Water Quality – Surface Practices	Meso	Pesticides and herbicides	3	Pesticide, herbicide, and insecticide use on the study area is high and a high concentrations of these chemicals were dumped/spilled by Pesticide Warehouse I – a Superfund site
		Micro	Industrial/ petroleum spills or dumping	3	5 Superfund sites, 0 Brownfields, 8 Toxic Release Inventory sites, 5 EPA registered cleanup sites and 64 Hazardous Waste sites. Illegal clandestine dumping was numerously documented.
		Micro	Leakage from underground tanks	3	27 listed leaking underground storage tanks
	Water Quality – Springs	At all Scales	Concentrations of harmful chemical constituents in springs	3	A study found nitrogen levels in the springs were at relatively high concentrations and fecal coliform and fecal streptococci bacteria were present. Additionally, Wells tested in Arecibo and several other municipalities in 1983 revealed ubiquitous contamination by nine trace-organic compounds, upon further analysis109 organic compounds in the ground water were detected.(76 or 70% were classified as priority pollutants)
	Water Quantity	Macro	Changes in water table	3	The municipality was divided by the two principal aquifer and withdrawal zones A and B. In zone A, five million gallons a day were withdrawn accounting for 11.1 % of the groundwater. Zone B had 60 mgd withdrawn accounting for 92.3% of the groundwater . Subsequently, saltwater intrusion extends several kilometers into the study area.

Table 2 Continued

Hydrology (continued)	Water Quantity (continued)	Micro	Changes in cave drip waters	LD	Insufficient data to assess indictor
Biota	Vegetation Disturbance	At all scales	Vegetation removal (% of total)	2	48-50% loss in original vegetation cover for the study area due to anthropogenic factors
	Subsurface Biota – Cave	Micro	Species richness (% decline)	LD	Insufficient data to assess indictor
		Micro	Population density	LD	Insufficient data to assess indictor
	Subsurface– Groundwater	Micro	Species richness (% decline)	LD	Insufficient data to assess indictor
		Micro	Population density	LD	Insufficient data to assess indictor
Cultural	Human Artifacts	At all scales	Destruction/ removal of historical artifact (% taken)	1	Two archeological sites removed artifacts. Additionally, minor damage on cave petroglyphs were observed.
	Stewardship of Karst Region	At all scales	Regulatory protection	1	Laws and regulations are in placed for protection and conservation. (Law No. 111, Regulation 6916)
		At all scales	Enforcement of regulations	3	Lack of enforcement to adequately protect karst is deemed low or virtually nonexistent by most NGO's and experts in the region and is evident by a myriad of documented disturbances
		At all scales	Public Education	1	Attempts made by NGO's and individuals
	Building infrastructure	Macro	Building of roads	3	One Expressway, two highways, 39 major roads and approximately 459 arterial streets
		Meso	Building over karst features	3	13% of the study area is developed which includes a large city. Mogotes are removed for roads and infrastructures.
		Micro	Construction in caves	1	Of the eight documented and four other known caves, two had construction within them (16%)

Geomorphology – Surface Landforms

Surface karst features are perhaps the most affected by anthropogenic actions because of the direct interface with human activities. These features are removed in large quantities for economic activities, such as quarrying and mining. Flooding caused by agriculture and hydroelectric dams can unnaturally change spring discharge rates and groundwater levels. Alteration of land by various infrastructure or surface practices can change stormwater flow into sinks and contaminate the groundwater by surface pollutants as well as infilled sinkholes that change natural drainage patterns. Finally, dumping trash and other wastes into sinks adds another source of contaminants that inevitably finds its way into the groundwater.

Quarrying/Mining – The assessment of this indicator is based on the number of mines and quarries within the study area. USGS GIS data (2005) was obtained from the Mineral Resource Data System which contained locations and descriptions of quarry/mine types. Several quarries from the aforementioned source were correlated with observed quarries from fieldwork. These quarries were large and open. In Arecibo there are three metal mines (gold, iron, and silica), 32 general limestone quarries, five stone and crushed and/or broken limestone quarries and eight sand and gravel limestone quarries (Figure 8).

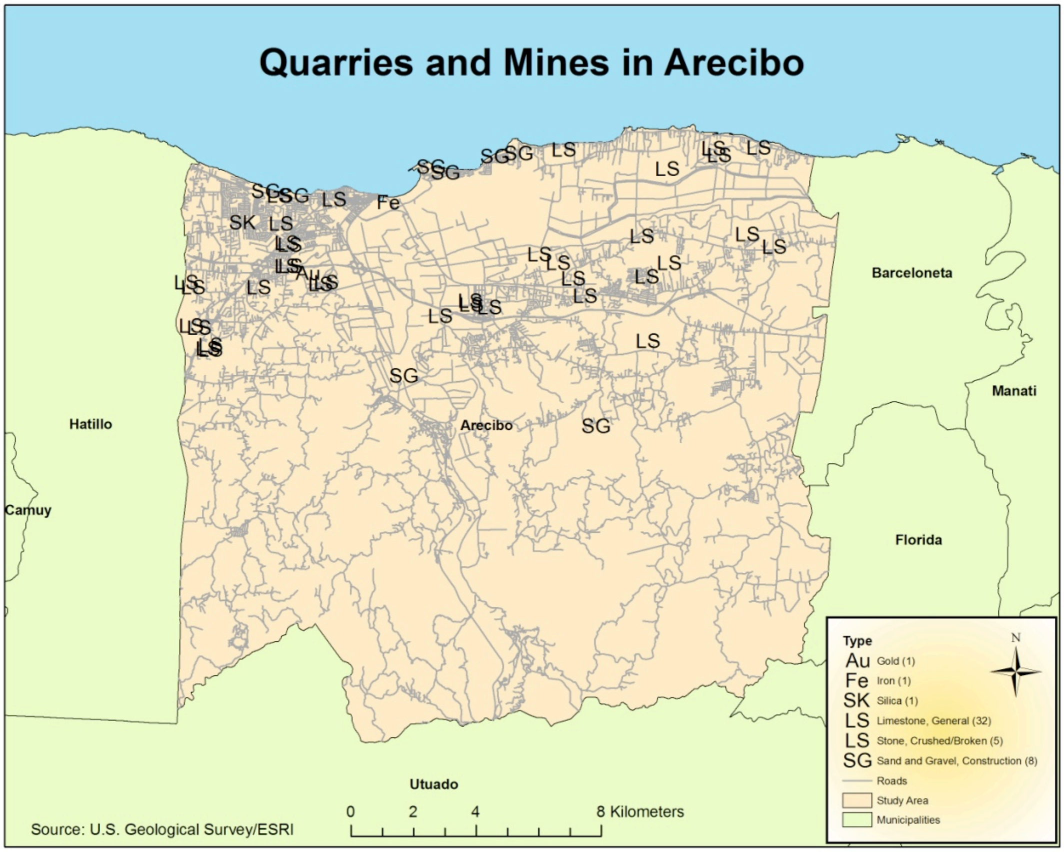

Fig. 8 Map of Quarry/Mine Locations in Arecibo (USGS 2005, ESRI 2008)

Altogether there are three mines and 45 quarries present within Arecibo. This is a widespread and severe impact for the study area. Additionally, fieldwork found evidence on quarry outcrops of damaged and destroyed solution conduits and potential cave passageways at four of the visited quarries (Figure 9). A score of 3 is given for this indicator based on the number of disturbances and widespread locations.

Fig. 9 Picture Mosaic of Two Arecibo Quarries (courtesy of Jason Polk 2010)

Flooding of Surface Karst – In south central Arecibo, the Dos Bocas hydroelectric dam and reservoir alters karst hydrology and unnaturally floods the river valley (Figure 10). This human built structure was constructed in 1942, is the second largest hydroelectric dam in Puerto Rico, and spans 30,420 acre-feet (Soler-López 2007, Hunter 1995). The original storage capacity was 37.5 million cubic meters, which has been reduced to less than half of that to 17.26 million by 2005 due to high sedimentation. The drainage area for the dam was reduced from 440 square kilometers to 310 in 1948 with the construction of the Lago Caonillas Dam (Soler-López 2007). This human built structure is a significant and severe disturbance to karst on a macro scale that alters the natural hydrological recharge downstream and can contribute to salt water intrusion down the coast along with changes in the water table.

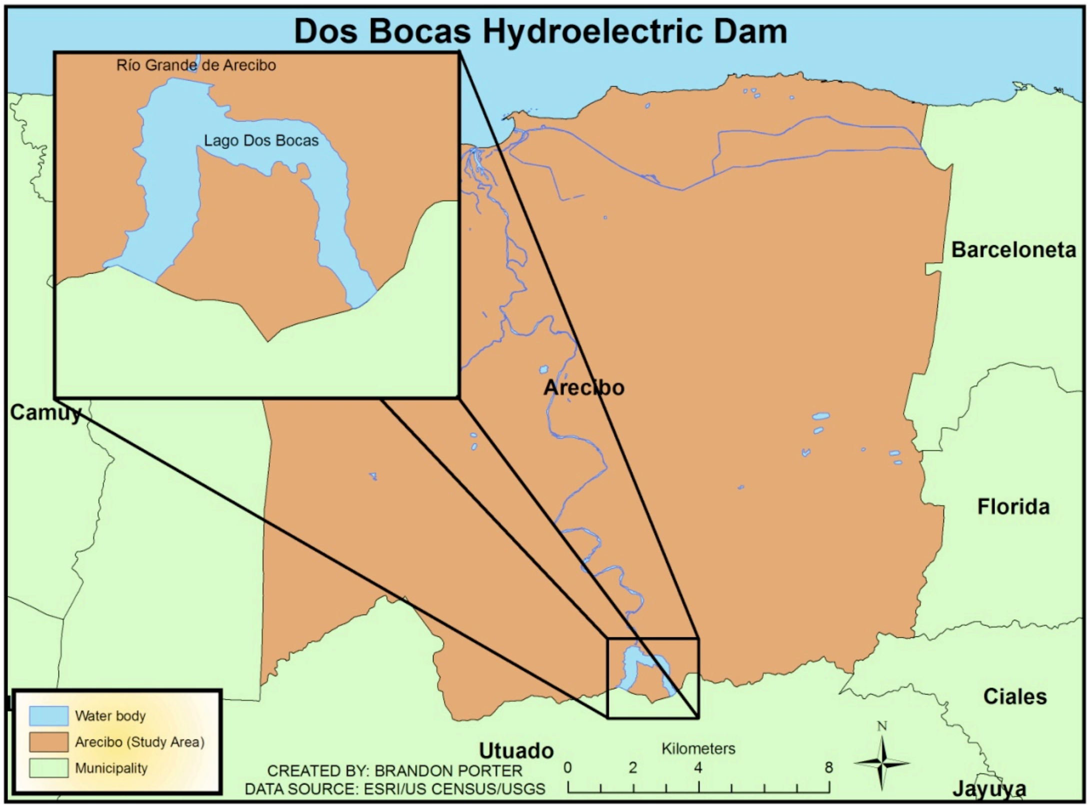

Fig. 10 Map of Dos Bocas Hydroelectric Dam (ESRI 2008, U.S. Census Bureau 2008(b))

In the Northeastern region of Arecibo, the country's largest wetland, the Caño Tiburones, is irrigated for crops and since 1949 has been pumped dry for recovery of land for agricultural use (Figure 11) (Gardiner et al. 2007). Commercial scale rice farming began in 1980 and accounts for 6,000 acres in Arecibo located in and around the wetland (Roman-Mas, 1988). However, in1998 the area was designated as a natural reserve by Puerto Rico Department of Natural Resources. A portion of the wetland is allowed to flood and is no longer pumped dry (Gardiner et al. 2007). For the aforementioned disturbances the score for this indicator is given a 3.

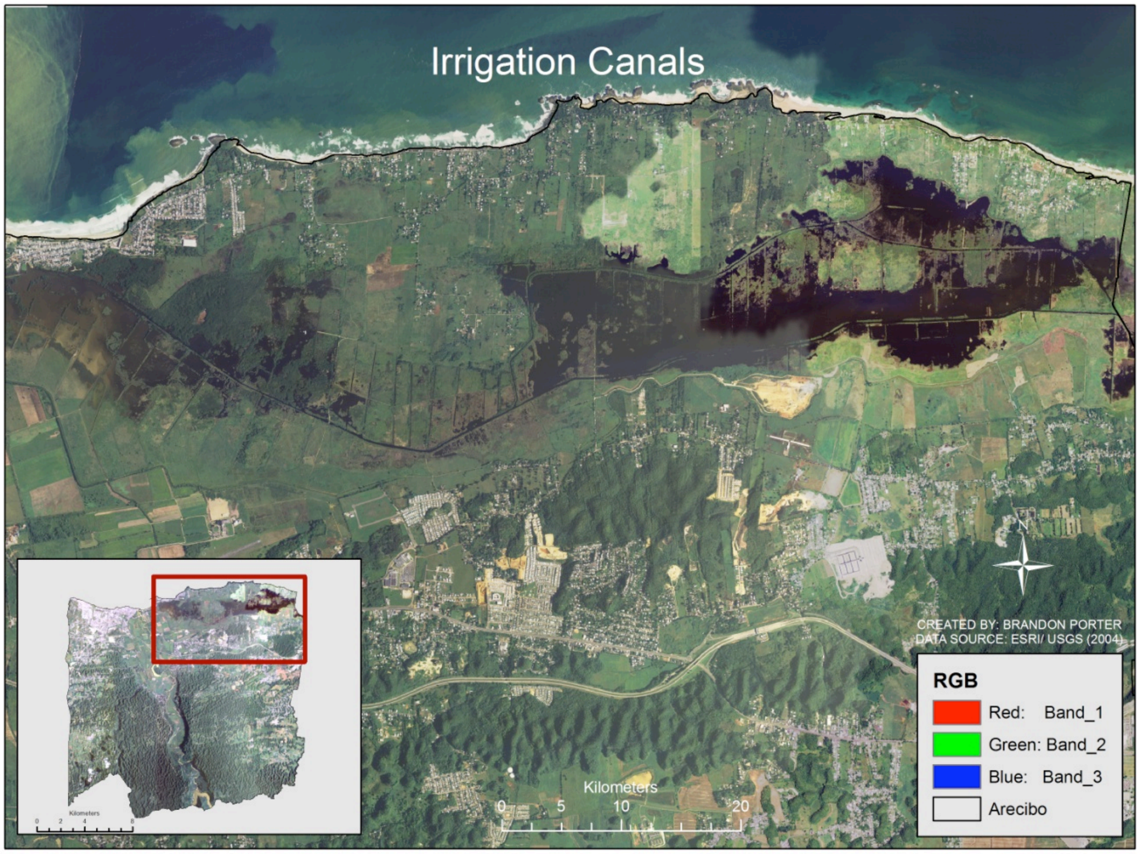

Fig. 11 Map Irrigation Canals (USGS 2004, ESRI 2008)

Stormwater Flow into Sinkholes – Number of sinkholes that are purposefully or accidently used for stormwater flow in the study area is unknown. Arecibo's Stormwater Management Program (SWMP) is currently in the process of a system inventory and analysis of drainage and water quality issues (EPA 2008). At present the municipality does not have a stormwater sewer map. However, it is the intent of Arecibo to complete the map due to the implementation phase of the National Pollution Discharge Elimination System (NPDES) (EPA 2008). Documentation of stormwater flow into sinkholes goes beyond the scope of this work and due to the lack of a stormwater sewer map and publications pertaining to this issue a LD is given for this indicator.

Infilling of Sinkholes – Sinkholes are routinely infilled so that various infrastructures can be constructed causing major alteration to karst landforms and hydrologic properties. For this indicator, topographic maps were obtained to determine the count of closed depressions that are assumed to be sinkholes. A 1964 and 1982 photo revised USGS topographic map of the Arecibo quadrangle were compared. In the 1964 topographic map, 656 sinkholes were counted and only 5 sinkholes were presumed to be infilled in the 1982 map due to new infrastructure built over pre-existing sinkholes.

The Arecibo quadrangle map does not contain the entire extent of the Arecibo municipality. Thus, five other quads were needed for proper assessment of the study area. Inconsistencies arose when obtaining these maps from USGS. Some were unavailable and others were of different years. An additional problem of assessing this indicator stemmed from the short temporal difference (18 years) of the two maps. This is not enough of a difference in time to accurately assess the percent of sinkholes infilled especially considering the amount of infrastructure present on the 1964 map. Remote sensing can be used to visually determine sinkholes or can be employed along with Digital Elevation Models (DEMs) and/or Shuttle Radar Topography Mission (SRTM) data and GIS techniques to delineate sinkholes (Siart et al. 2009). However, high resolution images such as aerial photos, Quickbird, IKONOS, etc. are needed for both methods because sinkholes can be a couple meters in diameter. Further complication arises from dense canopy cover and steep terrain making visual recognition of sinkholes difficult to impossible. Obtaining high-resolution images is costly and with the lack of data to determine sinkhole densities for all of the study area at or before 1964 this indicator was assigned an LD.

Dumping of Refuse into Sinkholes – Material that is either dumped or makes its way into sinkholes that clogs, pollutes, or deleteriously affects the aesthetics of the sinkhole were considered for this indicator (van Beynen and Townsend 2005). Within the study area, fieldwork was performed with the intention of indexing and assessing the state of every sinkhole we could find and had access to. The majority of the terrain is logistically unfeasible to traverse, covered with dense vegetation along with obstructed views by mogotes. Therefore, visiting a large percentage of the sinkholes goes beyond the scope of this work. Twelve sinkholes were found and assessed. Six of the aforementioned sinks had refuse observed within them at differing degrees of severity from commercial containers and wrappers, such as paper, cardboard boxes, food wrappers, etc., to large drums, refrigerators, microwaves, televisions and other household appliances, tires, and rusted automobile parts. One of the sinkholes visited houses the world's largest radio telescope, the Observatorio de Arecibo. The large sinkhole was utilized for its natural concave structure; however, considerable alteration was made by blasting and construction techniques. Although the telescope is not refuse, it is included in this indicator because of trash and debris that finds its way into the sink by tourist traffic and also because the dish of the telescope greatly alters precipitation and recharge by funneling all rain within the catchment area of the dish by way of a rectangular hole in the bottom (Figure 12).

Fig. 12 Picture of the Observatorio de Arecibo's Dish (taken by Brandon Porter 2010)

Although only a small percentage of the sinkholes present in the study area were inspected due to the restraints listed above, a reasonable assumption can be made about the state of the majority of the sinkholes that are away from transportation infrastructure and guarded from humans by steep and inaccessible terrain except by an experienced hiker. This would suggest pristine sinkholes that are very unlikely to have refuse deposited into them. Thus, the indicator was given a score of 1.

Geomorphology – Soils

Carbonic acid is formed when carbon dioxide and water combine in the atmosphere and biosphere (mainly the soil), thus becoming slightly acidic and capable of dissolving limestone. This process is essential to the formation and continued formation of karst landscapes. Therefore, it is important to protect and conserve soils. The practices of deforestation, agriculture, and urbanization increase soil erosion rates and anthropogenically limit or prohibit the natural acidity added from soil to percolating water that meets soluble rock interfaces. Moreover, urbanization and agriculture also compact soils by way of human activities and livestock that adds another component by limiting the quantity of water percolation and reducing aquifer recharge rates as well as inducing or increasing surface flooding. The following indicators assess the degree of anthropogenic impacts.

Soil Erosion – Deforestation and removal of indigenous flora for urbanization and agricultural practices have increased erosion rates within the study area. A 2003 USGS land use/land cover map of the study area showed that approximately 54% is covered by forest, open water, shrub/scrub, woody wetlands, and emergent herbaceous wetlands. Herbaceous land cover is approximately 23% and is assumed in this assessment to be land recovering from deforestation and other anthropogenic practices because natural land cover for this region is dense forest vegetation (Papp 1984, Sohn et. al., 1999). Cultivated crops and hay/pasture agriculture accounts for approximately 9% and developed land composes the remainder of approximately 14% (Figure 31). These surface practices coupled with steep gradients indicative of the area have resulted in anthropogenically increased erosion rates and are assessed to be a widespread high disturbance resulting in an indicator score of 2.

Soil Compaction – Compaction as a result of urban land use and agriculture are used in assessment of this indicator. The score was determined from the percent of land covered by these activities using a 2003 USGS land use/land cover map, as used in the previous indicator. Agriculture accounts for about 9% and urbanization about 14% of the land use, covering nearly a quarter of the study area (23%). This is a significant and widespread impact. It is important to note that the northern half of the study area is where the majority of the impacts are located and therefore more severely disturbed locally than in the southern half (Figure 13). Soil compaction as a result of these practices is significant and widespread. Thus, a score of 2 is given for this indicator.

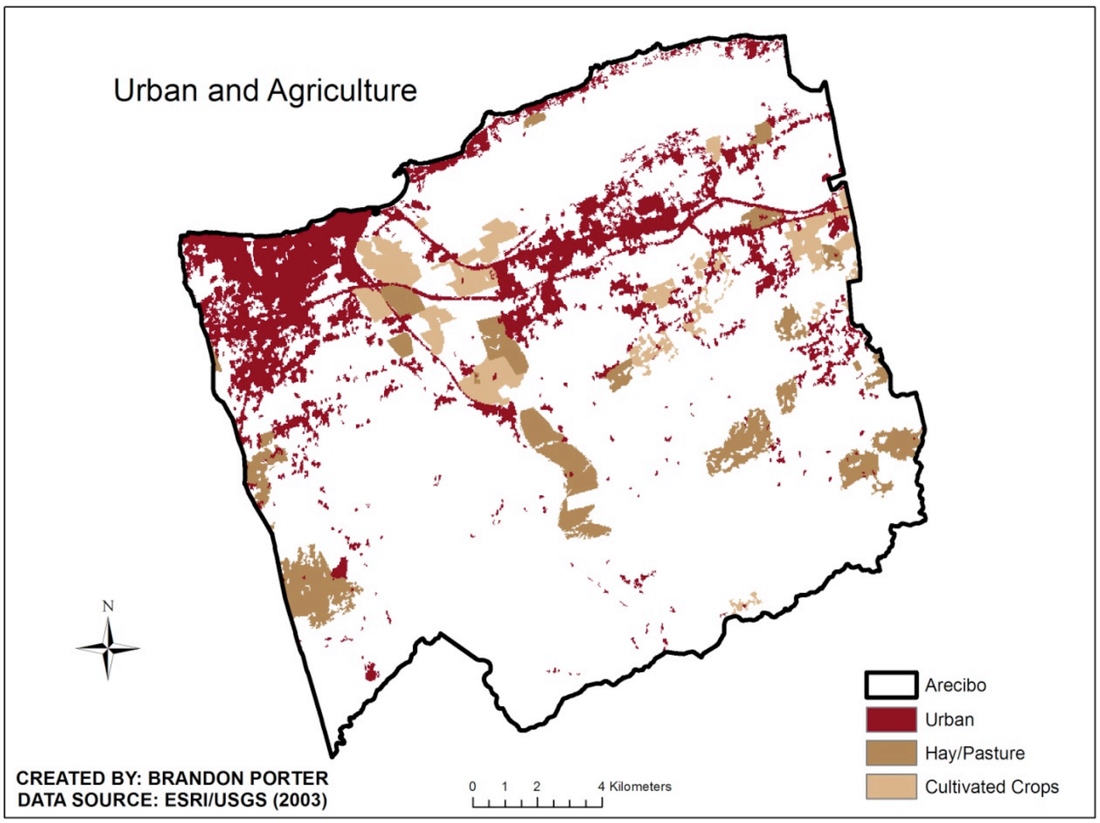

Fig. 13 Map of Urban and Agriculture Land use Land cover (USGS 2003, ESRI 2008)

Geomorphology – Subsurface Karst

Evaluation of the following indicators assesses the state of vadose and semi-phreatic caves. Disturbances that impact these unique ecosystems disrupt and harm cave biota and alter the natural formation of the cave passage and secondary formations such as, stalagmites, soda straws, etc. As a result, air flow, secondary formation development, and cave organism habitat, along with food supply and aesthetics of the cave passageways change (North 2007).

Flooding of Subsurface Karst – In Arecibo, flooding of subsurface karst is prevalent in the southern region of the municipality due to the Dos Bocas hydroelectric dam (Figure 15). The number of karst features inundated by the Lago Dos Bocas reservoir is unknown. However, this reservoir is surrounded by significant densities of mogotes (Figure 14) and assumable other karst features. The reservoir is a severe disturbance to karst in the southern region of Arecibo. For these reasons a score of 3 is given for this indicator.

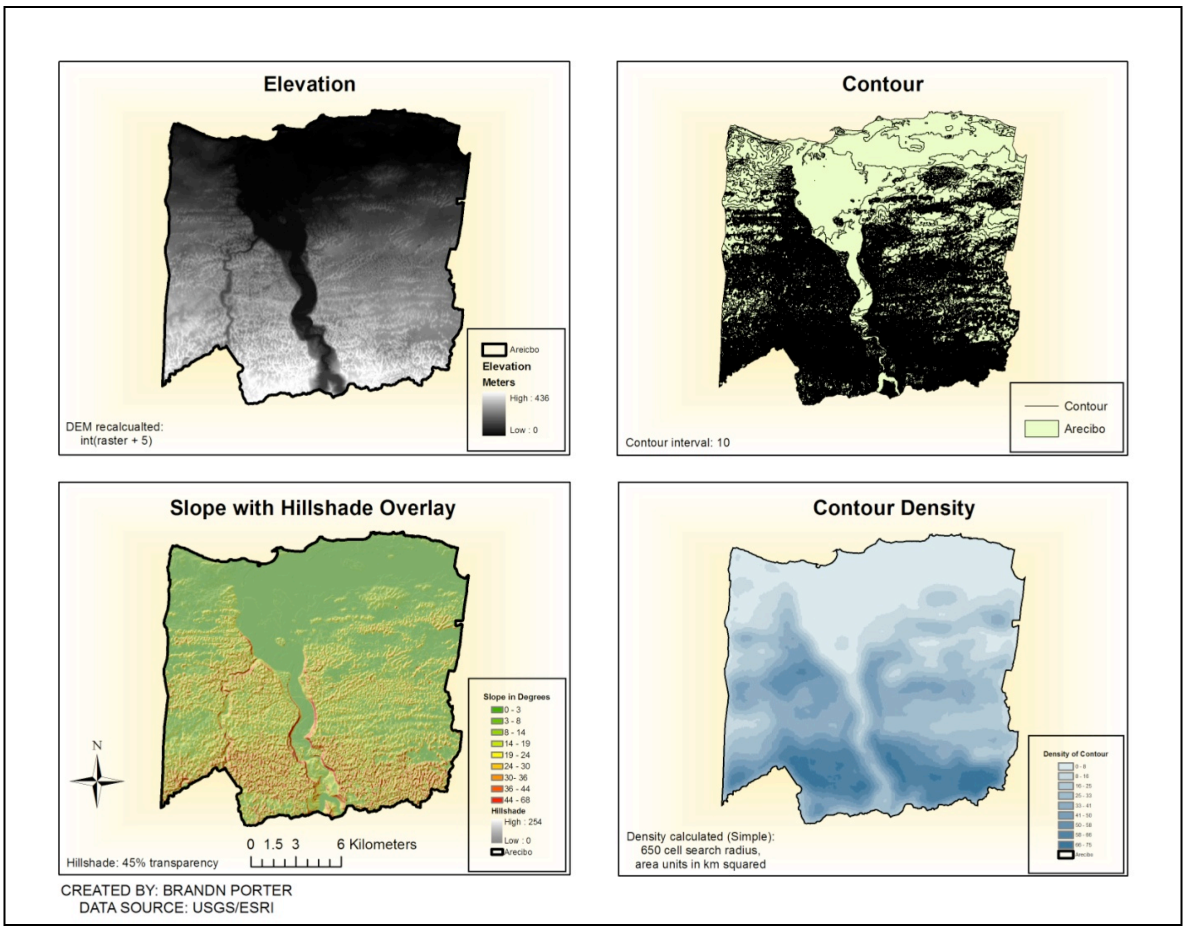

Fig. 14 Maps Showing Mogotes Densities (USGS 2009, ESRI 2008)

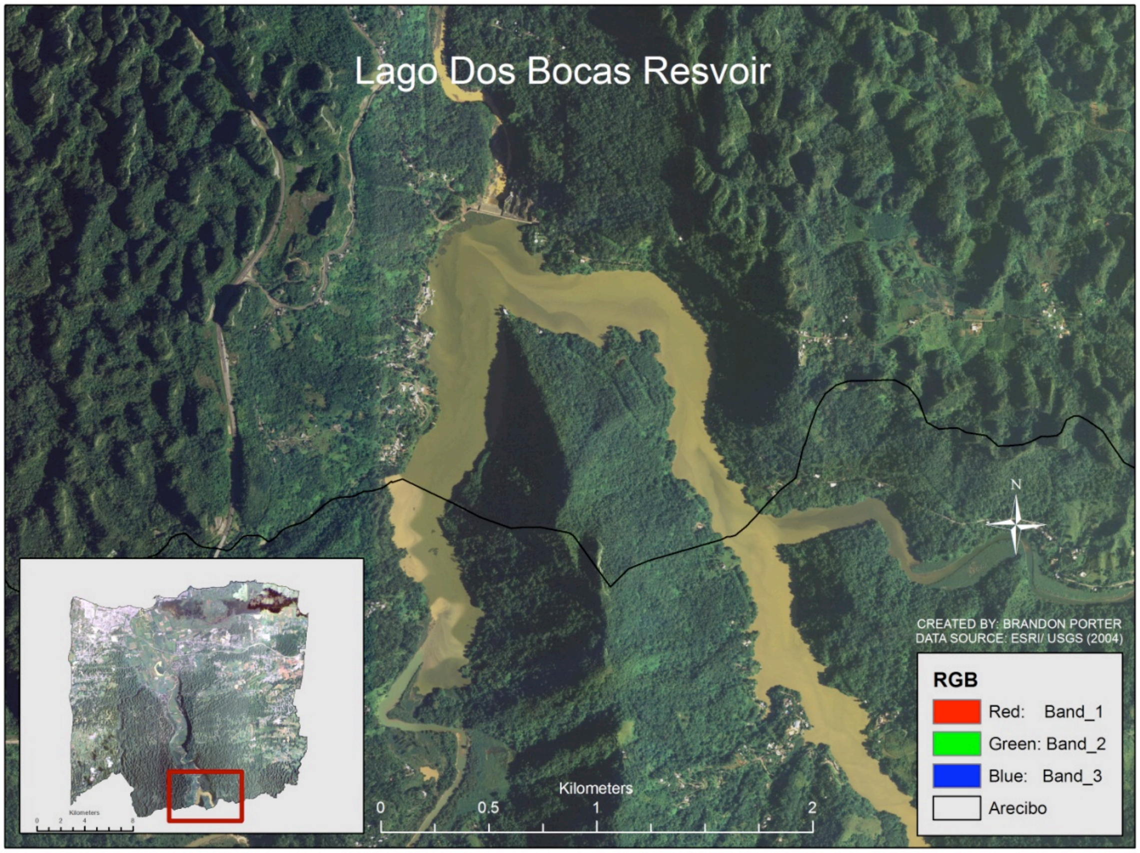

Fig. 15 Map of Dos Bocas in Orthoimagery (USGS 2004, ESRI 2008)

Decoration Removal/Vandalism – In Arecibo the number of vadose caves are unknown; however, two tourist caves: (Cueva de la Ventana and Cueva de los Indios) are present in the study area and receive high traffic. Cueva de la Ventana (The Window Cave) is very well known because of its lookout into a karst valley (Figure 16) but has no tourist infrastructure around or within it like the Río Camuy Cave, west of it. This cave was visited in January of 2010 during fieldwork to document decoration removal and vandalism in the cave. Some decoration removal evidence was present along with numerous examples of vandalism by carving and graffiti (Figure 17).

Fig. 16 Picture of Cueva de la Ventana (The Window Cave) (taken by Brandon Porter 2010)

Fig. 17 Picture Mosaic Cueva de la Ventana (courtesy of Jason Polk 2010)

Cueva de los Indios (Cave of the Indians) was also documented during fieldwork and contained numerous examples of carving and graffiti both from Indian petroglyphs and by present day tourists (Figure 18). However, due to the type of cave (sea cave) there were no formations/decorations to be removed or destroyed. The carvings are important archeologically and are the sole reason this cave is a tourist destination. However, the prehistoric carvings have a lasting effect on the cave and have consequently lead to the continue disturbance to this cave by people. Thus, it was included in the assessment of this indicator.

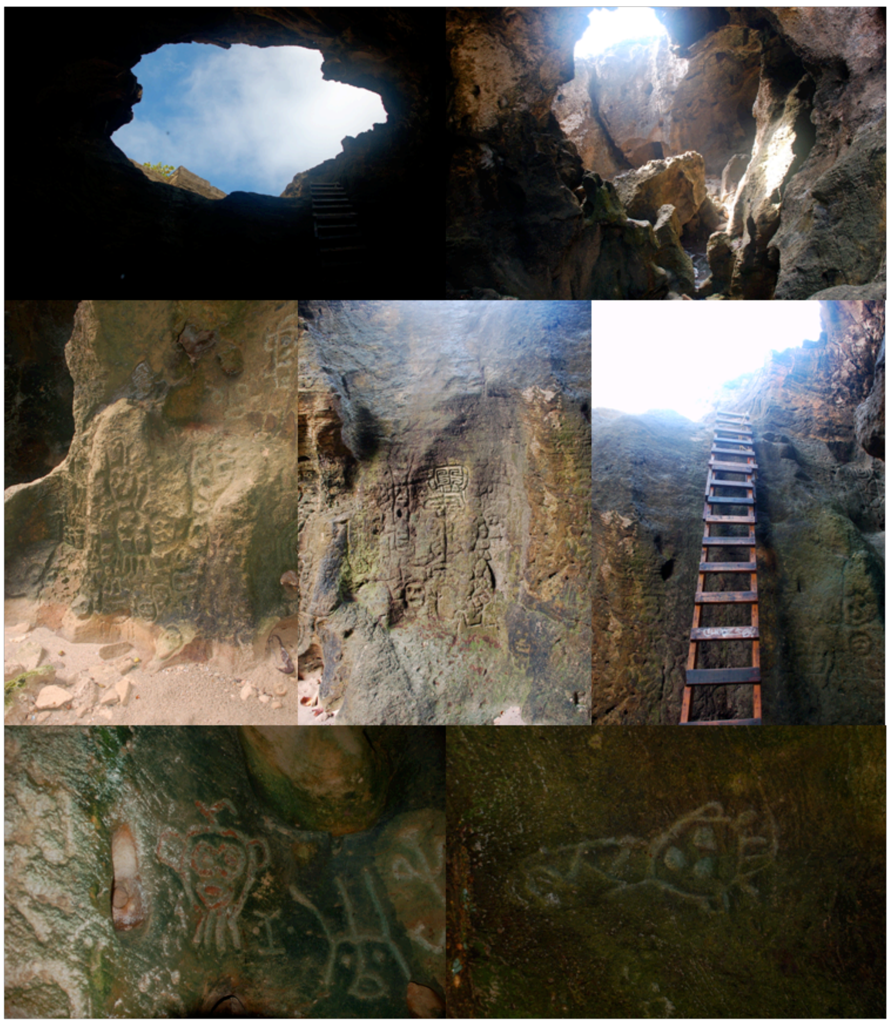

Fig. 18 Picture Mosaic Cueva de los Indios (Cave of the Indian) (curtesy of Jason Polk 2010)

Along with the tourist caves, two other caves and three shelter caves were documented and four caves were assessed through surveys. Of the eleven caves, five had decoration removal, vandalism, or both – accounting for approximately 45% of the caves. Experts who have surveyed or performed research in caves within the study area were surveyed to gather more data on this indicator and were similar to fieldwork findings. Thus a score of 2 was given for this indicator.

Mineral or Sediment Removal – Guano mining is the removal of bat fecal material and is a natural organic source of cave sediment. It is considered in this indicator. Guano mining is prevalent in Puerto Rico caves and has been most prevalent in Isle de Mona's flank margin caves (Frank 1998). The Camuy cave is nearby on the boarder of Camuy and Hatillo municipalities and was not heavily exploited for its guano (Nieves-Rivera 2003). However, in Arecibo, guano removal was widespread and was mined in almost every cave (Vale, personal communication, 2010). Other resources, such as minerals found within caves and cave sediments that are commonly mined have been minimally removed or impacted in the study area. Thus, the score of 1 is given for this indicator.

Floor Sediment Compaction or Destruction – Arecibo has two tourist caves that are frequently visited and experience a high volume of foot traffic. Cueva de los Indios is a flank margin cave and has an active tidal component that recharges sand sediment reducing the impact by not allowing accumulated traffic to compact sediments (Lace, personal communication, 2010). However, Cueva de la Ventana has significant floor compaction and rock erosion caused by tourists in approximately 50% of the upper passage way (Figure 19) (Lace, personal communication, 2010). Caves documented during fieldwork, other than the tourist caves, had little to no visible signs of human impact upon entering. However, natural erosion caused by flooding and rainfall was suspected to have erased any preexisting signs (Figure 20). Other known caves undergo minimal foot traffic by a few cave enthusiasts and surveyors and are only slightly disturbed (Lace, personal communication, 2010). Thus a score of 1 is given for this indicator.

Fig. 19 Picture of Cueva de la Ventana's Floor Compaction and Rock Erosion (courtesy of Jason Polk 2010)

Fig. 20 Picture of Solution Cave Documented during Fieldwork (courtesy of Jason Polk 2010)

Atmosphere – Air Quality

Anthropogenic changes in cave air quality can affect and alter karst passageways and secondary formations. For this reason, the indicators under this attribute assess the level of desiccation and condensation corrosion within known caves caused by artificial lighting, body heat, and respiration (North 2007). The indicators were assessed by documentation and fieldwork of caves as well as information obtained from surveys from experts who have explored, surveyed, or performed research in caves within Arecibo.

Desiccation – Arecibo has two tourist caves that receive high traffic with only one cave having speleothems (Cueva de la Ventana). Neither cave has lighting so the primary source for desiccation is body heat. Amount of desiccation incurred by this source is unknown but assumed to be moderate to high levels; however, it is the only heavily impacted cave in Arecibo by desiccation. Other caves, comprising the majority in the study area, receive very little traffic limiting desiccation to localized and not severe levels. A score of 1 is given for this indicator.

Human – Induced Condensation Corrosion – As previously stated in the above indicator, there are only two caves that receive high volumes of traffic and one cave that has secondary formations. Thus, moderate to high levels of human-induced condensation corrosion is only prevalent in one cave. The majority of the caves in the study area have very little traffic; therefore, the disturbance is localized and not severe and is given an indicator disturbance score of 1.

Hydrology- Water Quality from Surface Practices

Water is a necessary component of karst systems. Surface practices can pollute surface water, soil, and groundwater sources, thereby adversely affecting karst development as well as the health of karst aquifer ecosystems. For this reason, the extent of pollution from various sources needs to be assessed. The following indicators determine the severity of a wide range of pollutants found within the study area.

Pesticide and Herbicide Use – Synthetic and natural pesticides/herbicides utilized for agricultural practices, along with dumping, infiltrate into soils and groundwater impacting the health of ecosystems and people. According to the Colegio De Agrónomos De Puerto Rico website: “Seven of the nine most contaminated sites in Puerto Rico are in the karst district Arecibo…” (Rosaro 2003). Within the study area, pesticide and herbicide contamination is severe due to the superfund site Pesticide Warehouse I (PWI) and is exacerbated by agricultural and residential use.

The PWI facility is active and is located approximately 3 km south of Caño Tiburones. Since 1953, pesticides, insecticides, herbicides, and fertilizers for use on pineapple crops in the surrounding area were prepared and stored there (Gardiner et al. 2007). Samples from groundwater and soil collected in 1996 and 2003 were analyzed (Gardiner et al. 2007). Two pesticides, heptachlorepoxide and dieldrin, were detected in the groundwater and exceeded screening guidelines. Heptachlorepoxide at maximum concentration exceeded the Ambient Water Quality Criteria (AWQC) by one order of magnitude and dieldrin at maximum concentration exceeded it by four times. Nine pesticides were detected in the soil: aldrin, endrin, heptachlor, toxaphene, 4,4'-DDD, 4,4'-DDE, 4,4'-DDT, gamma-BHC (Lindane), and heptachlor epoxide. However, no screening guidelines are available for comparing the maximum concentrations found for these pesticides (Gardiner et al. 2007). Moreover, as stated above, these chemicals have been used on pineapple crops in the surrounding area increasing the amount released into the environment.

Additionally, low levels of pesticides, primarily composed of dieldrin, heptachlor and 4,4'-DDE, were found in the Lago Los Bocas reservoir on the other side of the study area to the south (Neal et al. 2005). This shows a widespread macro level impact of pesticide, herbicide, and insecticide use on the study area with high concentrations located around superfund site PWI. For these reasons a score of 3 is given for this indicator.

Industrial and Petroleum Spills or Dumping – Superfund and Brownfield sites along with other point source types are a source of hazardous leachate into the groundwater that deleteriously affect the environment. This indicator is assessed by number and overall pervasiveness of hazardous contaminates wrought by such sites within the study area. According to the Environmental Protection Agency (2010),“Superfund is the name given to the environmental program established to address abandoned hazardous waste sites. It is also the name of the fund established by the Comprehensive Environmental Response, Compensation and Liability Act of 1980…” (p. 1).

This program locates and investigates these sites and places them on the National Priorities List, so that appropriate remediation plans can be established and implemented. Brownfields are defined as, “real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant,” (USEPA 2010, p 2). Other sites not pertaining to the aforementioned produce and dispose of hazardous material into the environment. The EPA tries to regulate and report some of these industries by way of the Toxics Release Inventory USEPA (2010) which states:

> The Toxics Release Inventory (TRI) is a publicly available EPA database that contains information on toxic chemical releases and waste management activities reported annually by certain industries as well as federal facilities. The TRI program compiles the TRI data each year and makes it available through downloadable files and several data access tools (p. 4).

Hazardous waste is also reported to the EPA by the responsible parties and is defined by USEPA (2010) as: “waste that is dangerous or potentially harmful to our health or the environment. Hazardous wastes can be liquids, solids, gases, or sludges. They can be discarded commercial products, like cleaning fluids or pesticides, or the by-products of manufacturing processes,” (p. 1).

Arecibo has five Superfund sites, no brownfields, eight toxic release sites (Pharmacia & Upjohn Caribe Incorporated is both a Superfund and a toxic release site), five EPA registered cleanup sites, and 64 Hazardous Waste sites (Figure 21). Details of these sites and listed containments follow. These surface practices yield a severe and widespread impact.

Superfund Sites

The EPA added the Pesticide Warehouse I (PWI) site to the Superfund National Priorities List (NPL) on September 27, 2006 because hazardous chemicals were found in the soil and ground water. The warehouse stored and prepared pesticides with excess pesticides being disposed of on the ground where leachate from the waste contaminated the soil and ground water. Within a four mile radius of the site the ground water contamination potentially threatens public wells. According to the EPA site report “The Puerto Rico Aqueduct and Sewer Authority indicated that approximately 48,600 people are served by public supply wells within four miles of PWI.” Clean up of this site is further complicated “due to the complexity of karst terrain hydrogeology at the site…” (USEPA 2008, p. 8).

The Murcielago Pesticide Warehouse, Prla Superfund site has the following information listed: Removal Only Site, Removal assessment ended on 9/24/2003. The site was added to the Superfund National Priorities List (NPL) on September 27, 2006 because hazardous chemicals were found in the soil and ground water. The warehouse stored and prepared pesticides with excess pesticides being disposed of on the ground where leachate from the waste contaminated the soil and ground water. Within a four mile radius of the site, the ground water contamination potentially threatens public wells. According to the EPA (2008) site report states:

> The Puerto Rico Aqueduct and Sewer Authority indicated that approximately 48,600 people are served by public supply wells within four miles of PWI." Clean up of this site is further complicated "due to the complexity of karst terrain hydrogeology at the site… (p. 9).

The Murcielago Pesticide Warehouse-Prla Superfund site, Finca Las Lizas Superfund site, and Cambalache National Forest Superfund site have not undergone mitigation of contaminates and no contaminates are listed for these sites on EPA's Superfund site information system. The Pharmacia and Upjohn Caribe Incorporated site has completed physical cleanup activity and is awaiting deletion from the NPL.

Toxic Release Inventory

Kayser Roth Hosiery Incorporated released 60,000 pounds of Ammonium Sulfate (solution) into the receiving streams or water bodies in 1993. In 1994, 15,000 pounds of Ammonium Sulfate (solution) were released and given the designation of DISP NON METALS, which refers to the summation of a group of the methods that can be used to dispose of a metal or non-metal chemical off-site. The methods are: M10 Storage Only, M71 Underground Injection, M72 Landfills/Disposal Surface Impoundment, M73 Land Treatment, M79 Other Land Disposal, M81 Underground Injection to Class I Wells, M82 Underground Injection to Class II-V Wells, M90 Other Off-site Management, M94 Transfers to Waste Broker for Disposal, and M99 Unknown. No additional dates were reported or listed.

Puerto Rico Electric Power Authority Cambalache Combustion Turbine Plant released the following chemicals between 1998 and 2008 in various quantities through three media (AIR FUG - Fugitive or non-point air emissions, AIR STACK - Stack or Point air emissions, and DISP NON METALS): 1,2,4-Trimethylbenzene, Ammonia, Copper Compounds, Lead, Lead Compounds, Mercury compounds, N-Hexane, Naphthalene, Polycyclic Aromatic Compounds, and Sulfuric Acid.

Thermo King De Puerto Rico released the following chemicals between 1998 and 2008 in various quantities through two media (AIR FUG and AIR STACK): Chromium, Ethylene Glycol, and Xylene (Mixed Isomers). Maycom Amp Puerto Rico Incorporated released the following chemical between 1989 and 2008 in various quantities through one medium (AIR FUG): 1,1,1-Trimethylbenzene.The Cutler Hammer Electrical Company released the following chemicals between 1998 and 2008 in various quantities through several media (AIR FUG, AIR STACK, DISP NON METALS, RCRA C – Disposal to on-site RCRA Subtitle C landfills, And OTH DISP- Other on-site land disposal): Aluminum Oxide (Fibrous forms), Copper, Cyanide Compounds, Formaldehyde, Nickel Compounds, Phenol, Silver Compounds, Styrene, and Zinc Compounds. The Merch Sharp & Dohme Quimica De Puerto Rico released the following chemicals between 1993 and 2008 in various quantities through two media (AIR FUG and AIR STACK): Acetone, Naphthalene, Sulfuric Acid. Finally, the Pharmacia & Upjohn Caribe Incorporated released the following chemicals between 1998 and 2008 in various quantities through several media media (AIR FUG, AIR STACK and OTH DISP): Acetonitrile, Ammonia, Benzo (G, H, I) Perylene, Cyclohexane, Dichloromethane, Ethylene Glycol, Formaldehyde, Mercury, Methanol, Methyl Ethylketone, N, N-Dimethylformamide, N- Butyl Alcohol, N-Hexane, Polycyolic Aromatic Compounds, Pyridine and Toluene. The Superacuducto Filtration Plant released containments were not listed in the EPA's Toxics Release Inventory System.

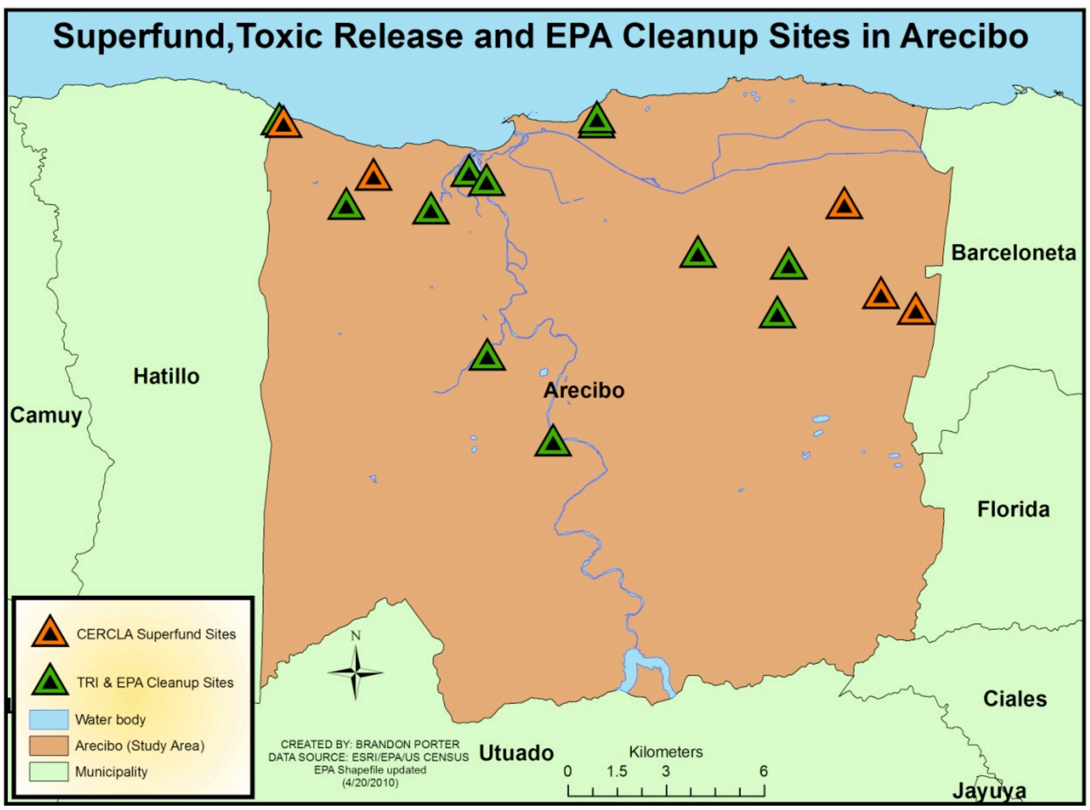

Fig. 21 Map of Superfund/Toxic Release Inventory/EPA Cleanup Sites (ESRI 2008, US Census 2008, EPA 2010)

Other surface practices that deleteriously affect water quality are legal and illegal dumping of refuse on a karst terrain. Arecibo has a large regional landfill that is located less than 30 meters away from Puerto Rico's largest coastal wetland the Caño Tiburones (Figure 22). Fieldwork revealed that some of the refuse from the large mound find its way into the wetland. In addition to this legal dumping site, dozens of illegal dumping locations were documented and refuse included anything from large appliances to batteries (Figure 23). For the aforementioned reasons, the disturbance to water quality is widespread and severe and given a score of 3.

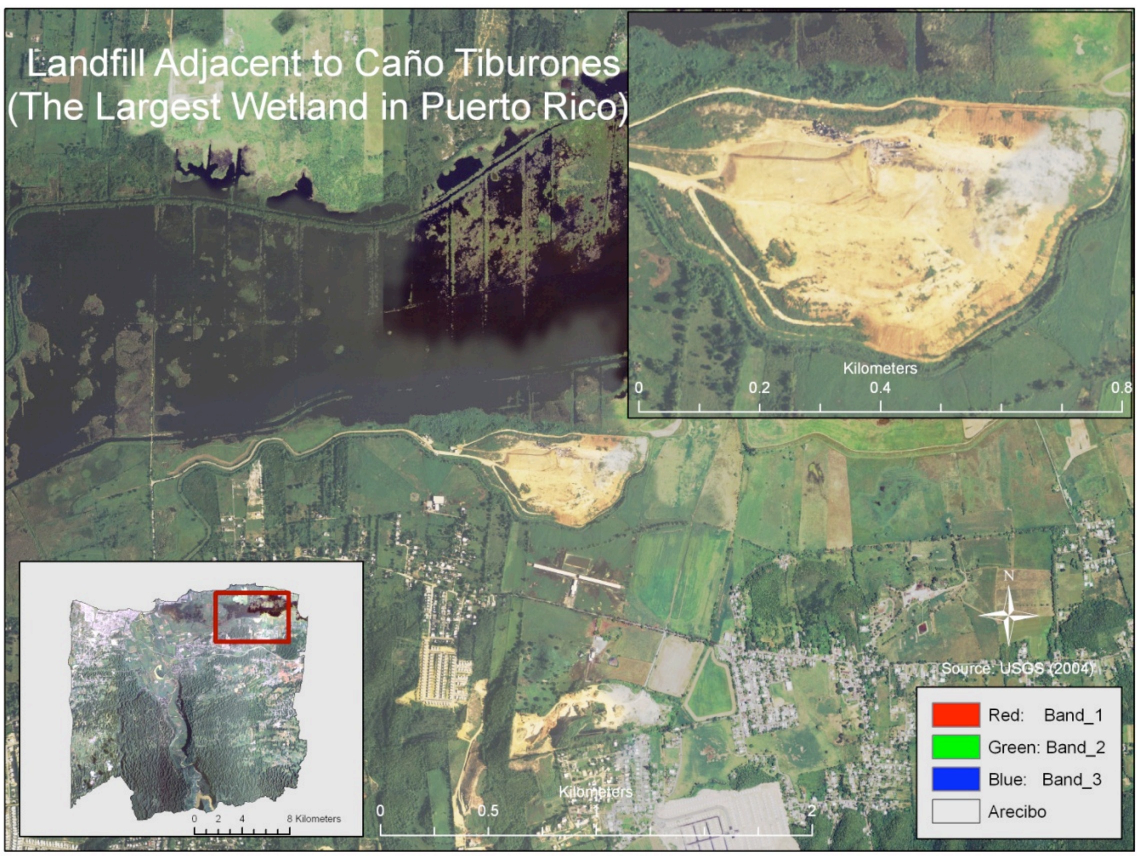

Fig. 22 Map of Landfill in Orthoimagery (USGS 2004)

Fig. 23 Picture Mosaic of Illegal Dumping of Refuse (taken by Brandon Porter 2010)

Leakage from Underground Tanks – According to a press release by the EPA (2010), "Petroleum releases from underground storage tanks can contaminate water, making it unsafe to drink, pose fire and explosion hazards, and can have short and long-term effects on people's health" (p. 1). In June of 1998 the Puerto Rico Land Authority (Autoridad de Tierras de Puerto Rico) agreed to properly remove all underground storage tanks on the island and pay $50,000 penalty for violations of federal regulations (Cahill 1998). In Arecibo, one filling station failed to have leak detection provided and was cited for this violation in May of 1997 (Cahill 1998). Upjohn Facility had a severe underground tank leak listed on the National Priorities List and designated a superfund site in 1984 (EPA 2010). The primary pollutants of concern were Volatile Organic Compounds (VOC's). However, a remediation plan was selected and the EPA completed construction in

September of 1998 (EPA 2010). To date, the EPA assures that contamination of groundwater migration is under control.

Leaking Underground Storage Tanks (LUST) are reported and made public in Puerto Rico by the Estado Libre Asociado de Puerto Rico, Oficina del Governador: Junta de Calidad Ambiental-División de Protección de Aguas Subterraneas. The system that oversees the underground storage tanks are delegated by the federal EPA. A LUST list obtained from the site above has 27 listed leaking underground storage tanks in Arecibo ("lust list" 2007). This signifies a widespread severe disturbance and results in a score of 3 for this indicator.

Hydrology – Spring Water Quality- Chemical concentrations in springs are increased by surface practices and disposal/use of harmful substances, such as, fertilizers, illegal dumping of refuse, groundwater injection disposal methods, leaking septic tanks, spills, along with any other practice that distributes harmful chemicals into the hydrologic system (North 2007). Impacts from various chemicals can range from more growth of algal blooms and/or bacteria to a myriad of biological problems in species dependant on the water.

Harmful Chemical Constituents in Springs – In karst systems, harmful chemicals found at springs are an indicator of pollution that shows the human impact on the quality of water. In Puerto Rico, there exists many springs that discharge significant amounts of fresh water and saline water that could be used to supplement other water supply sources. Until 1982, springs were not investigated for quality of water or magnitude of flow. A two-year study was conducted by the University of Puerto Rico, Department of Natural

Resources, and the US Geological Survey on the hydrology and geochemistry of the island's principal springs. Hundreds of springs exist, with the majority in the North coast limestone belt.

Of the 17 tested springs, 3 are within the study areas, which are La Cambija Spring at Caño Tiburones, Zanja Fria Spring at Caño Tiburones, and San Pedro Spring near the city of Arecibo. Nitrogen levels in the springs are at relatively high concentrations, but concentrations of phosphorus and organic carbon levels are low (Figure 24) (Guzman-Rios 1985). However, the 3 springs with the highest levels were not in the study area, but in the neighboring municipalities of Florida and Manati. Trace elements were in general low in springs that were not thermal. Additionally, this study found fecal coliform and fecal streptococci bacteria present in the majority of springs (Guzman-Rios 1985).

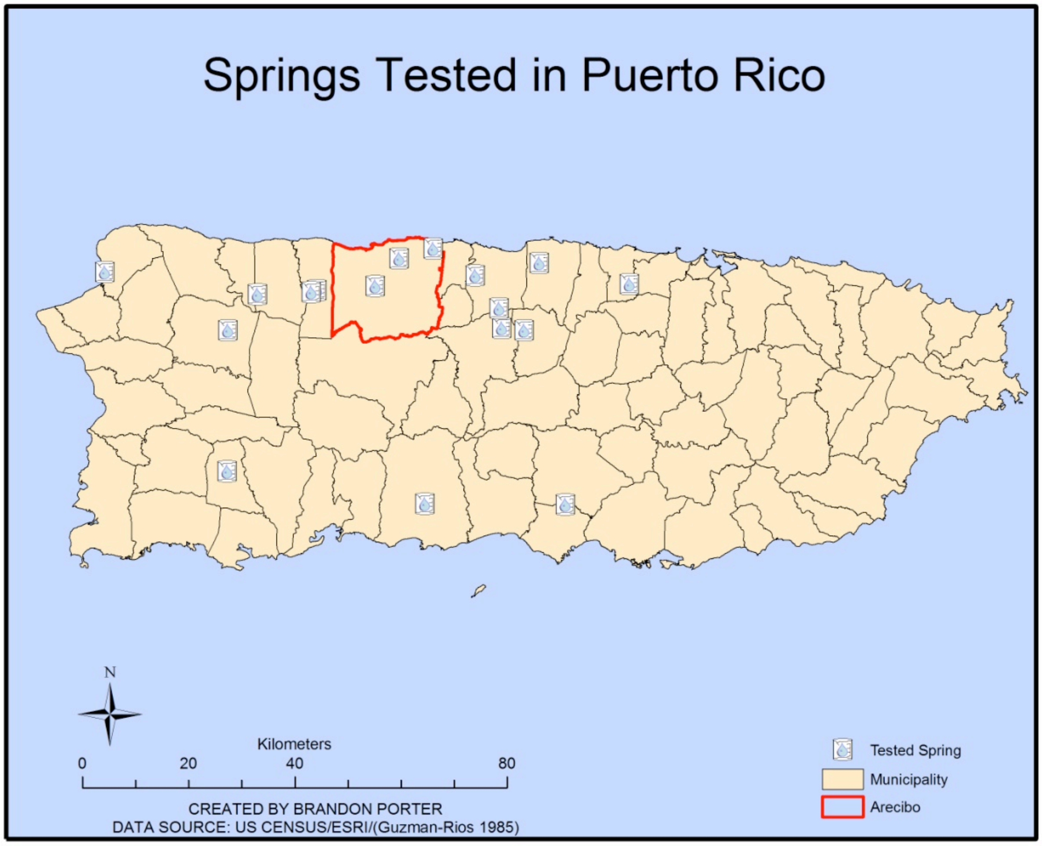

Fig. 24 Map of Tested Springs (Guzman-Rios 1985, US Census 2008, ESRI 2008)

Wells are another indicator of the quality of groundwater and were included in the assessment of this indicator. Wells tested in Arecibo and several other municipalities in 1983 revealed ubiquitous contamination by nine trace-organic compounds and "laboratory analyses detected 109 organic compounds in the ground water of which 76 or 70% were classified as priority pollutants" (Figure 25) (Hunter and Arbona 1995, p. 1350). Presences of Methylene Chloride, a solvent, were found at two wells in Arecibo (Guzman-Rios and Quinones-Marquez 1985). Contaminated springs and wells are a severe disturbance, resulting in a score of 3.

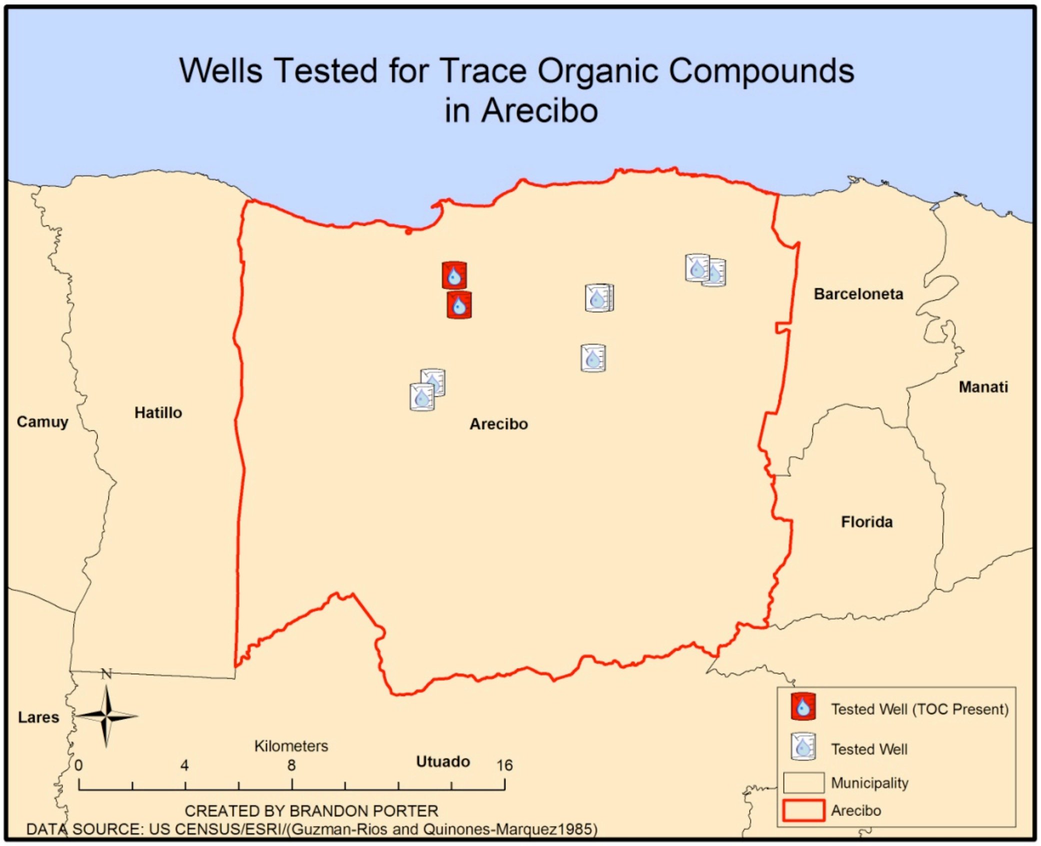

Fig. 25 Map of Tested Wells (Guzman-Rios and Quinones-Marques 1985, US Census 2008, ESRI 2008)

Hydrology – Water Quantity

Over-pumping an aquifer can potentially lower the water table and change flow directions impacting discharge rates of springs and streams. However, these fluctuations can also be caused by natural variations in precipitation rates brought by seasonality and climate changes (Starr & Cherry 1994). Therefore, examinations of anthropogenic disturbances are focused as to reduce the possibility of natural changes affecting assessment. Saltwater intrusion can occur in cases where pumping occurs on an island or coastal setting that limits the amount of available freshwater and introduces brackish waters into developing karst features.

Changes in Water Table – Arecibo has several known disturbances that affect the water table level. The Dos Bocas hydroelectric dam in the south of the municipality changes natural drainage and recharge rates in the Río Grande de Arecibo. This river is the largest surface stream in the Arecibo municipality and flows north from the dam until it meets the Atlantic Ocean. This is a macro level disturbance affecting a large area (Figure 26).

The municipality is heavily urbanized and dependant on freshwater from the aquifer. In 1980 daily withdrawals from the groundwater accounted for 43% of the water consumed in north and south coast aquifers and totaled 210 million gallons a day (mgd) (Hunter & Arbona 1995). In Gomez-Gomez (1987), the Arecibo municipality was divided by the principal aquifer and withdrawal zones A (west coast to Río Grande de Arecibo) and B (Río Grande de Arecibo to Río de la Plata). In zone A, five mgd (million gallons a day) were withdrawn accounting for 11.1% of the groundwater. Zone B was one of two zones where dependence on groundwater was the greatest and had 60 mgd withdrawn accounting for 92.3% of the groundwater (Hunter & Arbona 1995, Gomez-Gomez 1987). The amount of heavy pumping has increased the loss in the aquifer due to saltwater intrusion in Arecibo (Hunter and Arbona, 1995, Zack et al. 1988). USGS (2006) potentiometric maps are available for part of the study area; however, no previous maps are available to discern any changes from previous years (Rodriques and Gomez-Gomez 2008).

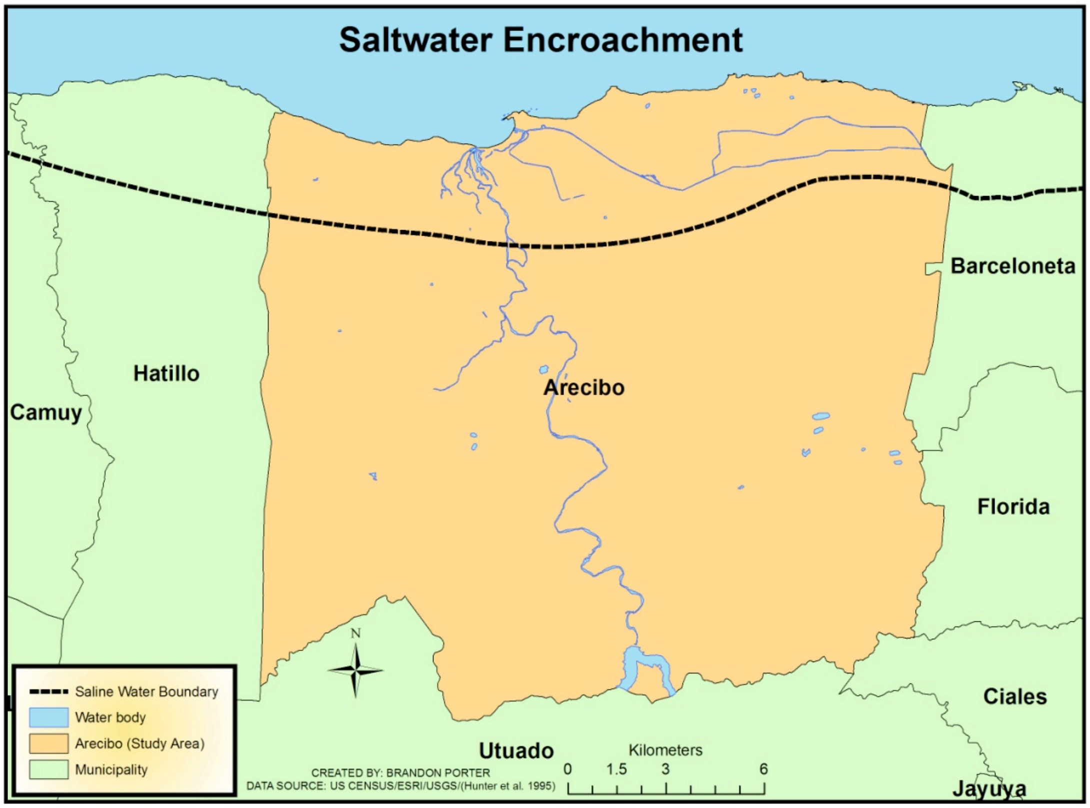

Fig. 26 Río Grande de Arecibo, Lago Dos Bocas reservoir, and saltwater encroachment boundary of dissolved-solids concentration larger than 2,000 milligrams per liter (modified from Hunter et al. 1995)

Another anthropogenic impact to the water table results from injection of excess streamflow into the saline aquifer for the purpose of storing water for use when surface-waters are minimal and to help prevent the inland migration of saltwater (Quiñones-Aponte et al. 1989). In a USGS water resources investigation, six injection-recovery tests were made that included injected volumes ranging from 0.6 to 6.6 million gallons for storage period ranging from 6 minutes to nearly 31 days (Quiñones-Aponte et al. 1989). Although these tests were designed to understand the feasibility of injecting, storing, and recovering the excess streamflow to aid in reducing some of the harmful impacts caused by heavy pumping, it affected the water table for those periods and was included in the assessment. Heavy pumping within the study area significantly changes the water table resulting in a score of 3.

Changes in Cave Drip Waters – Isotope analysis and acoustic counting of cave drip waters are quantitative methods to evaluate changes in drip rate and geochemistry. No research was found that employed these methods in the study area of Arecibo. However, a qualitative method can be used in lieu of these for the assessment of this indicator. Imperviousness of land cover can be an indicator of anthropogenic impacts that disallow water to naturally infiltrate into soils and groundwater limiting percolation of water into the system (see discussion on *Building over Karst*). Moreover, surficial waters such as stormwater can be altered significantly by impervious surfaces and change the natural flow of accumulated precipitation. However, a second component would be needed in order to properly make a conclusion on this indicator. The second component is the number of caves that underlie or are in close proximity and equal to or lower in elevation than anthropogenic impervious surfaces.

In Arecibo, there is no list of the number of caves that fall within the above criteria. During fieldwork, a number of caves were documented and were located in close proximity to infrastructure; however, these caves were higher in elevation than the impervious surfaces and received unobstructed rainfall. Thus, not enough data is present for assessment of this indicator and therefore was given an LD.

Biota – Vegetation Disturbance

Vegetation disturbance is caused by many practices, including but not limited to: urbanization, deforestation, clear-cutting for agriculture, logging, fire/controlled burns, and/or quarrying. These impacts deleteriously affect karst terrains by increasing soil erosion rates and the degradation of groundwater (North 2007). Also, removing vegetation decreases the amount of vegetal litter that is a component of soil and decreases the amount of carbon dioxide within the soil due in part to less organic material undergoing the decomposition process. The aforementioned changes affect the karst formation process by limiting and reducing important factors that influence development (North 2007). Because of this, it is important to understand the level of vegetation disturbance within the study area to better understand the impact to developing karst features.

Vegetation Removal - The assessment of this indicator is based on the percent of urban and agricultural lands using USGS land use/ land cover data of the study area, as with the soil erosion and soil compaction indicators, in addition to tree canopy cover.

Canopy cover of the study area derived from USGS's National Land Cover Database (NLCD) can be utilized to estimate the percentage of forested land by dividing the number of total pixel values (30m pixels) by the total number of pixels for the study area (Figure 27). This calculation results in approximately 48% of forested lands remain in Arecibo based on the canopy cover and approximately 46% based on the land use land cover data using a similar calculation (Figure 32). From this a conclusion can be derived from the reasonable assumption that most of the land cover in the tropical study area would have been forested before settlement in 1556. However, herbaceous lands can be natural in origin or can result from anthropogenic changes, such as, lands recovering from deforestation, clear cutting, abandoned cropland, nutrient loading, and invasive species (Papp 1984, Sohn et. al., 1999). In the study area, approximately 23% of the land cover is herbaceous and was assumed in this study to be recovering lands from anthropogenic changes because of the pixels (units that represent the land cover in raster images) close proximity to pixels that represent anthropogenic factors (i.e. developed, agricultural, etc.). Aggregation of the natural land cover of emergent herbaceous wetlands, open water, shrub/scrub, and woody wetlands accounts for approximately 8% of the study area which was removed from the total amount of land cover that could possibly be forested. Assuming that about 92% of the land cover of Arecibo would have been forested before settlement, 46-48% remains forested resulting in a 48-50% loss in original vegetation cover for the study area due to anthropogenic factors resulting in a widespread high disturbance. Thus, a score of 2 is given for this indicator.

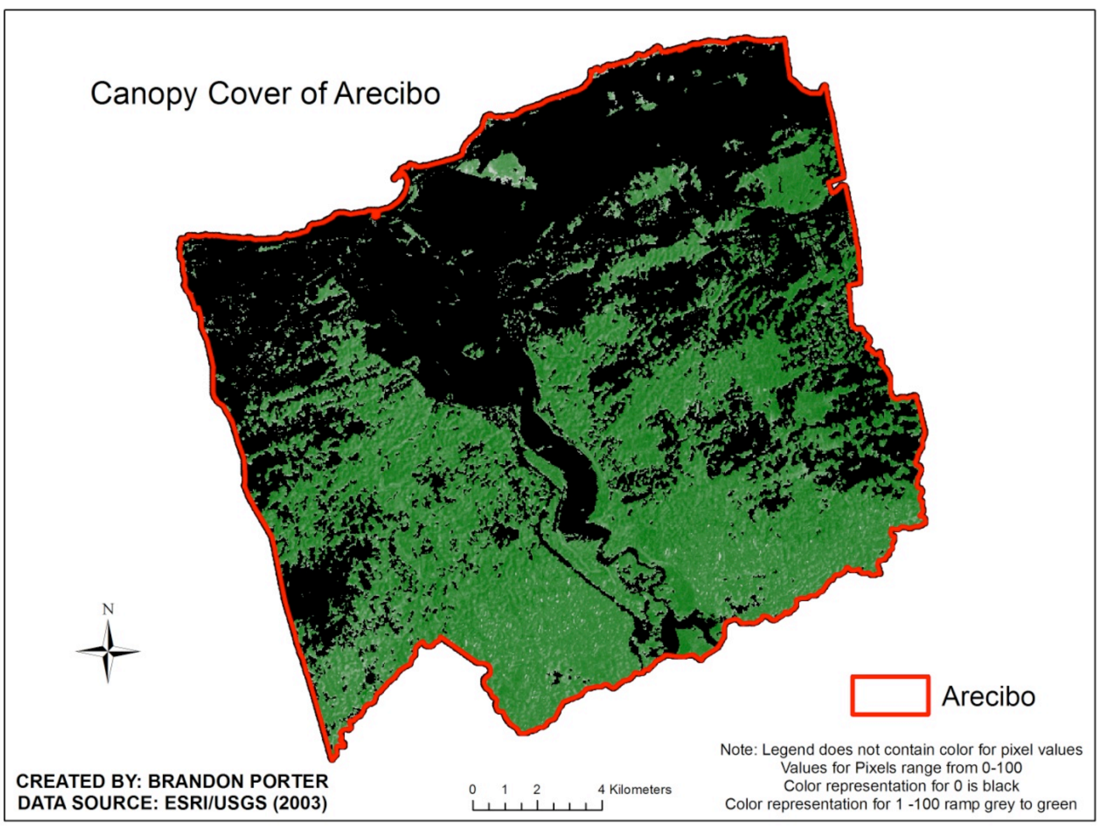

Fig. 27 Map: Canopy Cover (USGS 2003(c), ESRI 2008)

Biota – Subsurface Cave Biota

Subsurface cave biota are species that spend all or part of their life in caves and include but are not limited to: bats, swallows, fish, crawfish, salamanders, many insects, and bacteria. These organisms are important to cave ecosystems and can be an indicator of the health of the karst systems. Many of the species listed above are present in the study area; however, in order to assess the following indicators under this attribute '*Species Richness'* and '*Species Population Density*' data would need to be collected on number of species and population density of the present species in caves throughout Arecibo. These data are lacking from secondary sources and go beyond the scope of this work; therefore, a Lack of Data (LD) is assigned for these indicators and is reflected in the level of confidence for this study.

Biota – Subsurface Groundwater Biota

This attribute with its indicators of '*Species Richness*' and '*Species Population Density*' is assigned a Lack of Data (LD) for the same reasons listed above under the previous attribute.

Cultural – Human Artifacts

Human artifacts within caves can be historical materials and tools or in the form of petroglyphs inscribed on cave walls. Removal of artifacts can disturb the karst environment by displacement of cave sediment, floor compaction, disturbing local biota, and increasing the likelihood of desiccation and condensation corrosion. Other artifacts such as petroglyphs can be destroyed by carving and graffiti that also impact the karst environment negatively in addition to disturbances listed above.

Destruction or Removal of Historical Artifacts – Historical artifacts that are destroyed or removed including petroglyphs on cave walls are included in the assessment of this indicator. In the study area several documented sites have had removal of historical artifacts. Two pre-Colombian habitation sites were studied and analyzed (removed artifacts) for scientific purposes (AR-38-Tanamá Site; Ar-39-Río Tanamá Site) located on the north side of the Río Tanamá; a small tributary of the Río Grande de Arecibo (Pagán Jiménez 2006; Carlson and Steadman 2009).

Petroglyphs are "rock carvings that can be found on river boulders, walls of caves and rock shelters, and on stone slabs associated with aboriginal 'juegos de bola' or dance plazas" (Frassetto 1960). Many of these artifacts have been removed by collectors and caves have also been disturbed for procurement of artifacts throughout Puerto Rico (Frassetto 1960). Cueva de los Indios is a tourist cave known for its numerous carvings and was designated a Natural Reserve in 1992 by the Planning Board of Puerto Rico (Miní 2005). Fieldwork examined these petroglyphs and found that no discernable damage has taken place except for occasionally cases of graffiti and that they were well-preserved (Figure 28). For these reasons, a score of 1 is given for this indicator.

Fig. 28 Pictures of Cueve de los Indios' Carvings (courtesy of Jason Polk 2010)

Cultural – Stewardship of Karst Region

Regulatory protections and enforcement of those regulations, as well as public education can show a semblance of the importance of a karst terrain by a governing body and/or the populous. Those individuals or groups who wish to protect karst resources act as stewards for karst and are vital for the protection and education of human actions on the karst environments. Moreover, initiatives taken by the Arecibo municipality or groups that disseminate information about the significance of karst environments and how people can minimize their impact on it are equally as important for its protection.

Regulatory Protections – Laws that prohibit or limit the disturbance to karst terrains or specific features are considered in the assessment of this indicator. Important legislation was passed to protect karst terrains and features. Under the statues and regulations for Puerto Rico; Title 12: Conservation, Subtitle 5: Environment, there are two chapters

(122, 122A) that directly deal with karst issues. The first law was enacted on July 12, 1985, and is referred to as Law No. 111, p. 384, § 4 : § 1143c A second law was enacted on Aug. 21, 1999 and is No. 292 § 4. Descriptions and prohibitions/penalties of these laws are detailed in the appendix A at the end of this work.

Legislation was introduced before the 107th Congress that sought protection to Puerto Rico's karst in November 2001(H.R. 3213) proposed to

> …authorize the Secretary of Agriculture to acquire and manage lands in the Commonwealth of Puerto Rico to provide for the protection of critical aquifers and watersheds that serve as a principal water supply for Puerto Rico, and for other purposes (p. 8).

This bill recognizes the importance of the unique geological formation of this karst region and states: "The Karst Region is threatened by development, which, if unchecked, could permanently damage aquifers supplying fresh water and cause irreparable damage to natural and environmental assets that are unique to the United States and Puerto Rico" (H.R. 3213 2001, p. 9). This bill also recognizes that Puerto Rico has one of the highest population densities in the U.S. and that the Karst Region possesses extraordinary ecological diversity that includes several endangered and threatened species. The purpose of this Act (H.R. 3213)states:

> … to authorizes the Secretary of Agriculture, in cooperation with the Commonwealth of Puerto Rico to undertake a program of land conservation, acquisition, and research to protect and manage the geological and ecological values of the Karst Region, with particular

> emphasis on the maintenance of biodiversity within a tropical forest ecosystem and protection of the aquifers with are vital to the health and well being of the citizens of Puerto Rico (p.14).

This proposed bill was never implemented and in a previous session of Congress the bill did not pass and was cleared from the books (Library of Congress 2010).

Another bill was brought before 108th Congress in June, 2003 (S. 1256) and was cited as the Puerto Rico Karst Conservation Act of 2003. The bill (S. 1256) sought to protect the critical aquifers and watersheds that serve as a principal water supply for Puerto Rico in addition to protect the tropical forests of the Karst Region, and for other purposes (Library of Congress 2010). However, this bill also never became law for the same reason as previously stated above (Library of Congress 2010).

Regulation 6916 was added in 2004 and its purpose states (Rodriquez Rivera 2004):

> To regulate the extraction, excavation, removal, and dredging of the components of the earth crust called sand, gravel, rock, soil, silica, calcite, clay and any other similar component of the earth crust that is not regulated as an economic mineral, in public or private land, within the geographical limits of the Freely Associated State of Puerto Rico (p. 61)

The contents of this regulation explain the processes for applying and obtaining a variety of permits to conduct the activities regulated within it, and a number of regulations on how such activities should be carried out, including extraction, detonations, transportation and exportation. It also states that such permits may be suspended or revoked if the stated regulations are not followed.

Lastly, the most recent bill; H.R. 672: Puerto Rico Karst Conservation Act was introduced in January of 2007 to the 110th Congress. This bill sought to authorize the Secretary of Agriculture to acquire, protect and manage resources in and adjacent to the Karst Region of Puerto Rico to protect and conserve water quality and aquifers along with ecological, geological, fish and wildlife and other natural values of the Region. It was also referred to Committee, yet never survived Congressional session and therefore was never became a law and was cleared from the Federal Registry (Library of Congress 2010).

In addition to the aforementioned laws and regulations that directly affect karst environments in Puerto Rico, there exist a number of US environmental laws and regulations that are applicable in Puerto Rico that indirectly affect karst features such as, the Clean Water Act and Endangered Species Act. These national policies coupled with direct legislation for the protection of karst are important for this region. However, as previously discussed several bills were not passed that would have increased the overall protection of Puerto Rico's karst. For this reason, in addition to the loopholes that allow circumvention of some protection policies, a score of 1 is given for this indicator.

Enforcement of Regulations – Assessment of this indicator involves determining if the previous laws and regulation in the above indicator are enforced and to what degree (i.e. minimally, strictly). Indirect national legislation is enforced by EPA Region 2, which states:

> "…is committed to its mission of enforcing the federal laws that protect public health and the environment. Throughout our history, we have relied on a strong, aggressive enforcement program as the centerpiece of our efforts to ensure compliance with national environmental laws" (EPA, "enforcement", p 1).

This is evident in the study area, as there are multiple superfund sites and toxic release sites that are strictly monitored and are in various stages of the mitigation process (see *Industrial and Petroleum Spills or Dumping* discussion).

Examples of enforcement of regulations that could include the study area of Arecibo and show positive results, include: in a November 2007 EPA news release, the EPA "continued to bring more facilities in Puerto Rico into and beyond compliance with federal laws that protect public health and the environment in fiscal year 2007" (Cahill 2007). In that period these actions resulted in almost $1.8 billion spent in pollution control and cleanups. Moreover, the EPA issued 87 administrative orders to correct violations of regulations (Cahill 2007). Actions taken will help reduce pollution in the air, water and land by 51 million pounds. In the EPA Region 2, which also includes New Jersey, New York and the U.S. Virgin Islands exceeded the enforcement of program accomplishments of the previous year of 2006. "For example, the amount of money spent by the regulated community to build pollution abatement facilities and conduct environmental improvement measures increased over 1300%, from $285.9 million to over $4 billion. The volume of pollution reduced through enforcement actions rose by 95%, from 35.7 million pounds to 69.7 million pounds. The amount of civil penalties collected from non-complying facilities increased by 102%, from $5.6 million to $11.3

million, and the number of projects undertaken by the regulated community was up by 62%, from 21 to 34" (Cahill 2007).

Enforcement and Compliance History Online (ECHO) through the EPA displays facilities that are monitored for a given area in the U.S. In Arecibo, there are 47 facilities that have been monitored. Of the 47 facilities, 11 were inspected in the last year, 3-two years ago, 5-three years ago, 4-four years ago and 2 were inspected beyond ten years ago ("Enforcement & compliance" 2010). This shows an overall increase in enforcement of national laws and regulations that indirectly affect karst within the study area in the last twenty years.

Commonwealth laws that directly and indirectly affect karstic environments are enforced at a state level by the Department of Natural and Environmental Resources of Puerto Rico (DNER) which regulates a wide range of anthropogenic activities through approximately 78 special laws administered solely by the DNER (SIPE 2007). The duty of this government unit is to harmonize economic development with protection of the natural environment. Some of its responsibilities are to protect resources and natural systems of importance, such as: caves, sinks, and, in general, the karstic region which includes being responsible for the control of anthropogenic activities (SIPE 2007). However, in order to access the system of reports, one must be an authorized user. For this reason a detailed examination of enforcement of regulations at a state and local level could not be attempted.

Abel Vale Neves, President of Citizens for the Karst, an organization that aims to protect karst in Puerto Rico's North Karst Belt, strongly believes when asked about

DNER's enforcement of regulations; "…they do nothing, unless hell breaks loose and they try to do some public relations to give the impression they are doing something. Just like any other thing in politics 'follow the money'" (Vale, personal communication, 2010). Enforcement of regulations regarding karst is present; however, the lack of enforcement to adequately protect this resource is deemed low or virtually nonexistent by most NGO's and experts in the region and is evident by a myriad of disturbances that have been documented in this work. Thus, a score of 3 is given for this indicator.

Public Education – Public awareness of karst environments and the impacts people have on their own environment can help to reduce disturbances and create stewards. Assessment of this indicator includes both governmental and private programs that aim to protect the karst environment for this area, as well as an analysis of how effective these programs are at reaching the populous. Puerto Rico is considered to be an associated free state. For this reason, the state falls under the jurisdictions of both the commonwealth laws and federal environment regulations that can at times conflict (Santana 2010).

In an EPA press release, the organization applauded environmental champions in Puerto Rico. Environmental Quality Awards were presented to 14 projects in Puerto Rico. The persons awarded were referred to as "exemplary environmental stewards" who had gone above and beyond for environmental progress (EPA 2009, p. 2). However, of the 14 projects, only two were considered to have an impact in the study area: an author of a children's storybook series that provides children with information about global warming and an environmental reporter who "has helped to make the environment an issue that every paper in Puerto Rico covers" (EPA 2009, p. 4).

A Daily Sun (2009a) article stated that: "several environmental agencies and academic groups joined efforts to set up an National Environmental Education Strategy (ENEA in Spanish) in Puerto Rico in an aim for more sustainable society" (Daily Sun 2009a, p. 1). The goals of these organizations are to empower the communities to help protect their environment. María Fernández stated in the article (Daily Sun 2009a):

> "Puerto Rico is one of five Latin American countries without a national public policy for Environmental Education. In the United States, The National Environmental Education Act of 1990, empowers the U.S. Environmental Protection Agency (EPA) to provide environmental education in schools and communities and to help nonprofit organizations, environmental, and educational institutions to empower students with sustainability knowledge"(p. 2).

As previously mentioned in an above indicator, a local non-governmental and non-profit organization, Citizens for the Karst, Inc, is an important group that heads off karst violations and aims to educate the public on the vital resource. An article by the Daily Sun in late 2009(b) explained that this group along with others came out against proposed administrated regulations that would allow commercial industries to remove rock within protected areas under specific conditions that would potentially violate or circumvent Law 292 of 1999 via regulation 6916 of 2004 (see Figure 29 for law and regulation specifics) (Daily Sun, 2009b). In the article, the stewards claim that the government is not heeding its own Department of Natural and Environmental Resources study which states that just 35% of the karst zone should be completely preserved with all land extraction banned. The proponents for development on these protected areas criticized the study for suggesting that any development should be banned in the conservation area and that it would stunt the island's economic development (Daily Sun 2009b). The House passed a substitute to House bill 2566 that is said to attack the highly sensitive ecological area and potentially nullify the study by the DNER in September 2008 that would encourage development in that zone (Daily Sun 2010a). However, the bill failed in July of 2010 (Daily Sun 2010b). The Citizens for the Karst are cautious about the victory and believe that citizens should remain alert that the amendments may be approved without the benefit of public hearings. Other possible contributions for public education were sort after, such as, caving groups that can have programs or conduct presentations to inform the public. However, no examples of this type of education were found.

Development on protected karst areas remains a concern for interested parties. However, due to efforts made by concerned citizens for public awareness of karst issues, public education is present in the study area. Also, local media outlets disseminate information on the importance of karst terrains and possible threats to it. Thus, a score of 1 is given for this indicator because of the efforts made to inform the public. However, it is this researcher's opinion that public education in the study area could be greatly increased in the schools.

Cultural – Building Infrastructure

Urbanization is the process by which people construct residential, commercial, and industrial infrastructure to fulfill specific needs. Urbanization has many impacts on a karst environment including, but not limited to: infilling of sinkholes, soil compaction, surface flooding, and change in aquifer recharge rates. Highways and major roads contribute significantly to the overall anthropogenic impact of infrastructure because they take up the largest overall surface area of any urbanization practice. This practice is also the source of the largest groundwater contamination from stormwater runoff (North 2007). The following indicators are assessed by estimating the anthropogenic impacts of urbanization in Arecibo through GIS shapefiles and documented road cuts with abandoned roads throughout the study area.

Building of Roads – In Arecibo, there is one Expressway, two highways, 39 major roads and approximately 459 arterial streets (Figure 29). The roads collectively have a severe and widespread disturbance on karst; however, some of the roads constructed impact the karst terrain far greater than others. An example of this is PR-10, which cuts through dense mogotes where large quantities of rock were blasted away and removed to make the highway (compare Figure 14, Figure 29). This is a severe disturbance resulting in a score of 3 for this indicator.

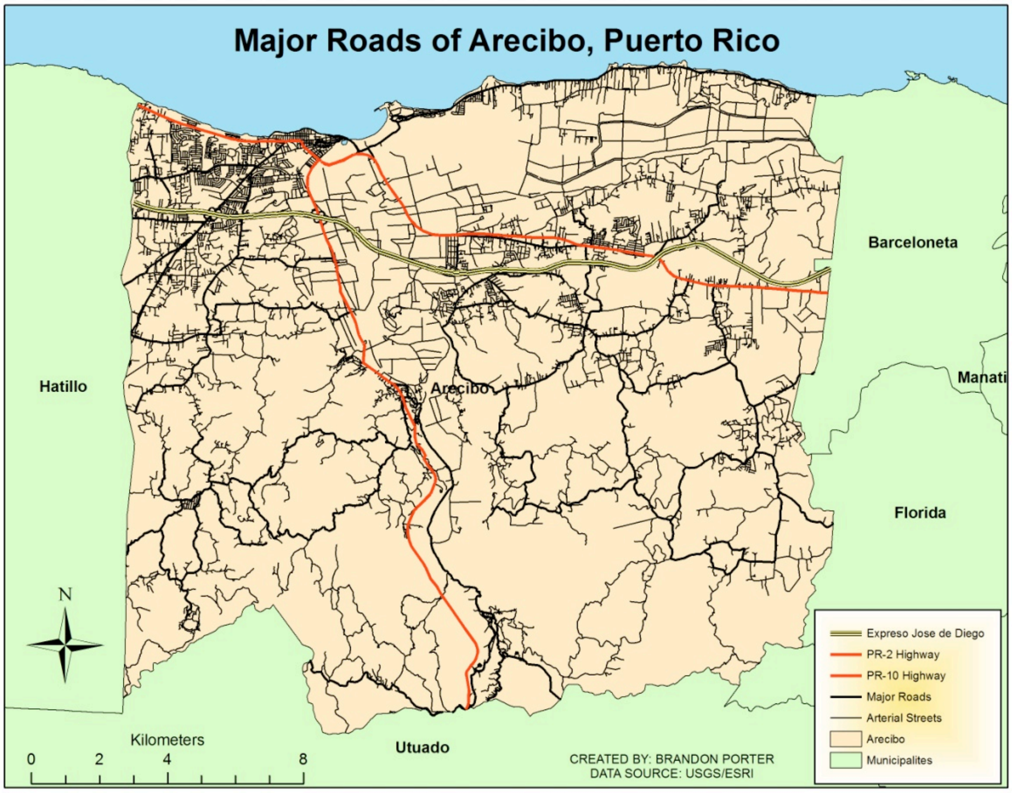

Fig. 29 Map of Major Roads in Arecibo (USGS 2005, ESRI 2008)

Construction within Caves - The evaluation of this indicator is based on the percent of caves within the study area that had evidence of construction and the degree of impact the construction had on the cave. To establish the degree of severity the construction had on the cave, the construction had to fall into three proposed levels of severity: significant alteration to the cave (i.e. construction of walkways, enlargement of cave openings, large amount of foreign material brought into cave), moderate alteration to the cave (i.e. lights, few handrails, small amount of foreign material brought into cave), light alteration to the cave (i.e. gates).

Of the eight documented and four other known caves (Cueva Sorbettos, Cueva Culebrones, Cueva Dos Chorros, and Nacimiento Opiolla) two had construction within them (16%) (Kambesis, personal communication, 2010). The two tourist caves of

Arecibo, Cueva de la Ventana and Cueva de los Indios, had no construction within the caves. Three other caves were documented with one having been gated (light alteration) and the others had no construction. Three shelter caves were also documented with one made into a shelter for storage (moderate alteration) (Figure 30). Therefore, a score of 1 is assigned to this indicator.

Fig. 30 Picture of Shelter Cave with Construction (taken by Brandon Porter 2010)

Building over Karst Features – According the US Census the estimated population of Arecibo in 2009 was 102,770 up from the 100,131 for the 2000 census. This is an increase in the year 2000's population by approximately 2.6%. The estimated population density in 2009 is 815 per sq mile (315 per km^2). Arecibo is among the five most heavily populated municipalities in Puerto Rico and is considerably urbanized in the northern half of the municipality. According to USGS land use/ land cover data, approximately 13% of the study area is developed (Figure 31).

Various infrastructures and building practices were observed during fieldwork that were not only built over features but required the removal of them. For example, mogotes' tops are removed for building of subdivision and highways. Another example is large infrastructures that also remove and or built on mogotes; such as the Dos Bocas hydroelectric dam and the radio observatory. These building practices cause severe disturbance to the karst terrain.

Imperviousness of an area can indicate building of infrastructure and can be useful in determining impacts to karst. Impervious surfaces are predominantly artificial surfaces that cover land and disallow the infiltration of water into the soil negatively impacting the environment (Arnold et al. 1996). These impervious anthropogenic structures are mainly comprised of pavements such as concrete, asphalt, stone, and rooftop materials. However, soils compacted by urban practices are highly impervious as well (Arnold et al. 1996). Impervious surfaces caused by infrastructure alter many factors that are often deleterious to karst environments. Moreover, impervious materials cause or increase stormwater runoff that carries non-point surface pollutants into the groundwater and waterways. This is the nation's leading threat to water quality (EPA 1994). To exacerbate this problem, karst terrains can greatly increase the rate in which stormwater flow enters the groundwater through sinks and epikarst features. The USGS imperviousness of Arecibo correlates with the development from the USGS land use/land cover and is approximately 12.3% (Figure 32). Building over karst is a severe disturbance to the study area and results in a score of 3 for this indicator.

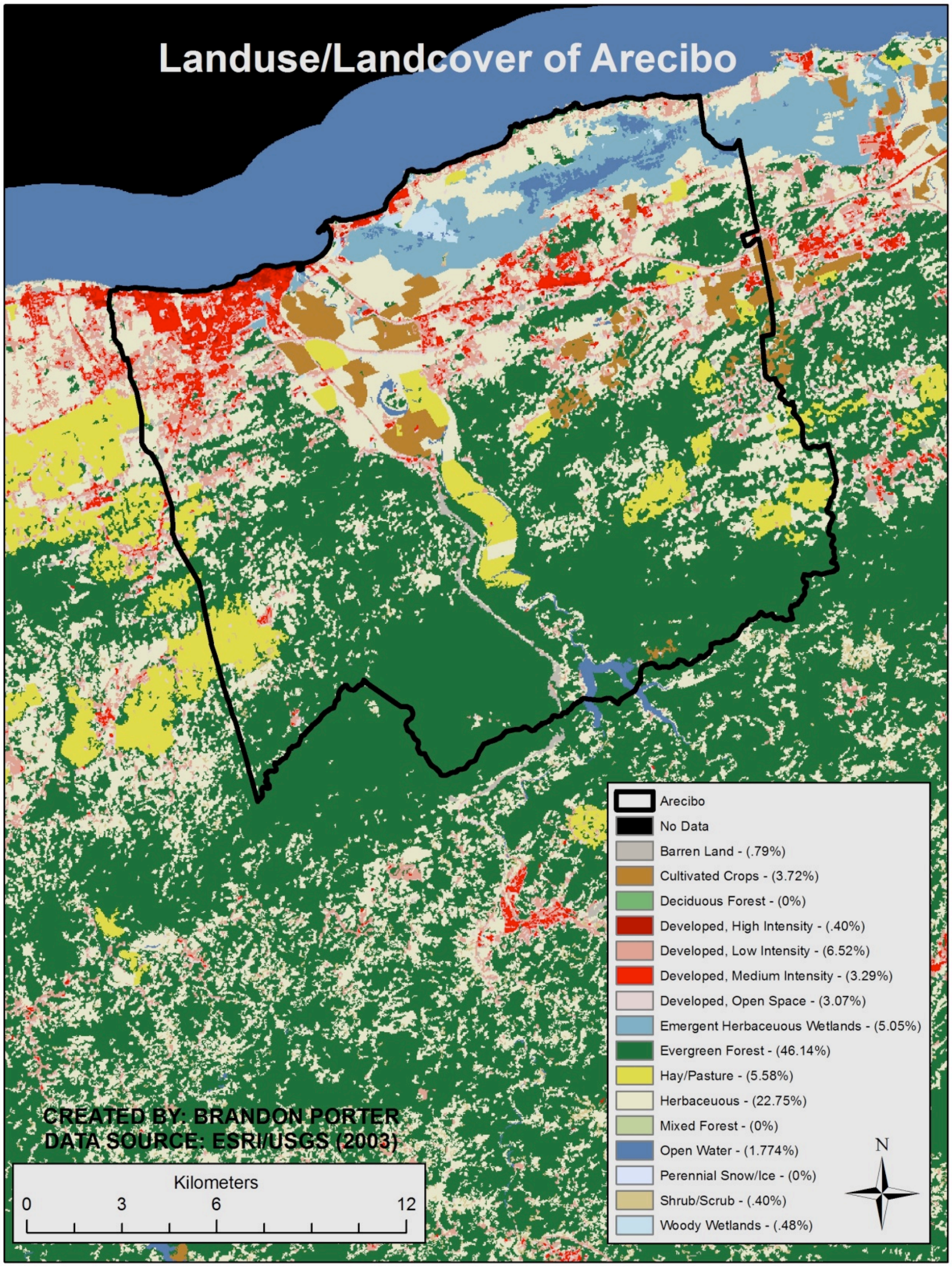

Fig. 31 Map: Land Use/ Land Cover of Arecibo (USGS 2003(a), ESRI 2008)

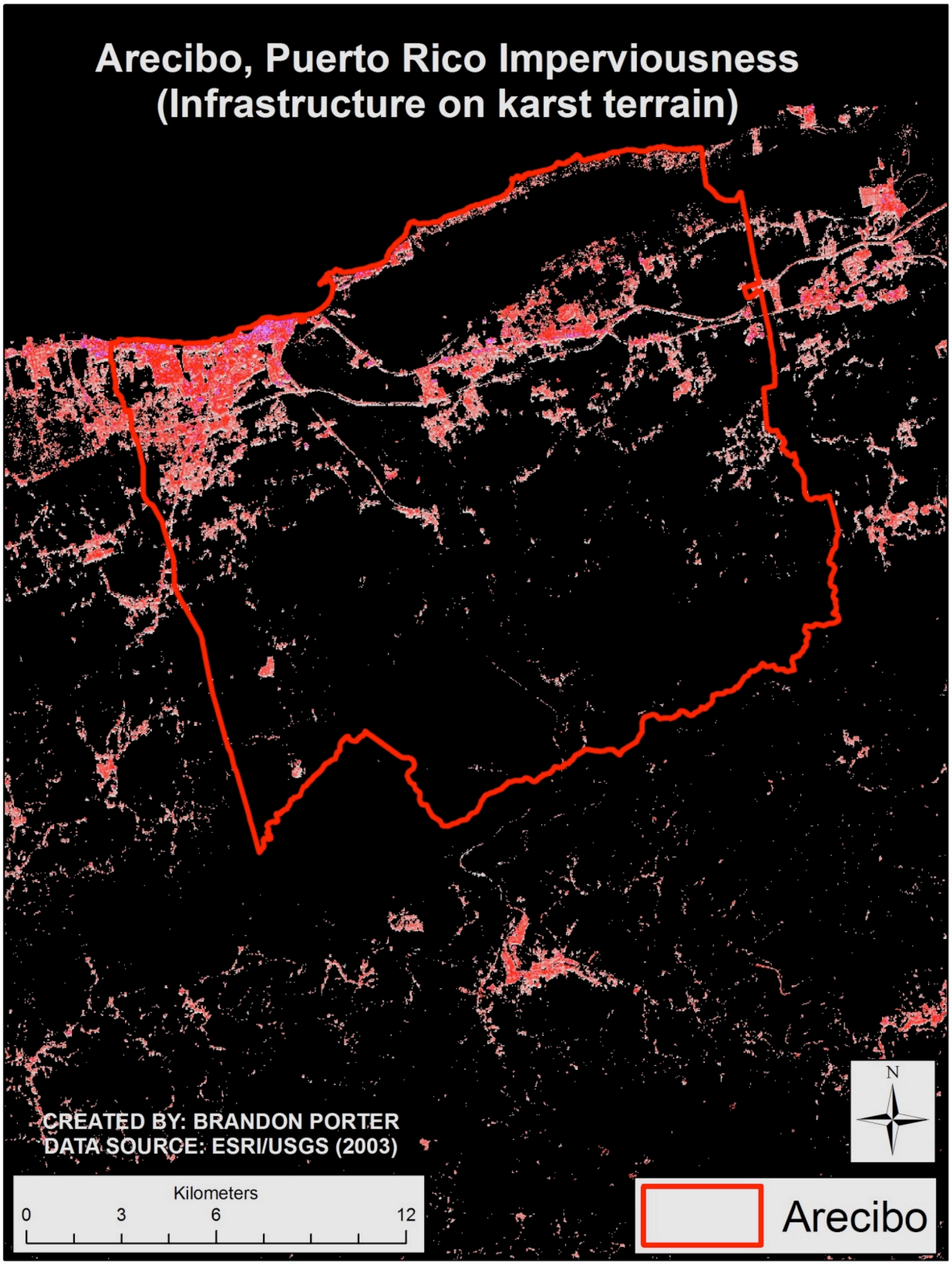

Fig. 32 Map: Imperviousness Surfaces in Arecibo (USGS 2003(b), ESRI 2008)

Degree of Disturbance and Levels of Confidence for Original Method

The disturbance scores for each indicator and total disturbance score for the study area are shown in Table 3. Explanation of the score and level of confidence in the score follows.

Table 3 Summation of Indicator Scores for Each Indicator and Total Disturbance Scores for Arecibo

Indicators	Arecibo
Quarrying/Mining	3
Flooding of Surface Karst	3
Stormwater Flow into Sinkholes	LD
Infilling of Sinkholes	LD
Dumping of Refuse into Sinkholes	1
Soil Erosion	2
Soil Compaction	2
Flooding of Subsurface Karst	3
Decoration Removal/Vandalism	2
Mineral or Sediment Removal	1
Floor Sediment Compaction or Destruction	1
Desiccation	1
Human-Induced Condensation Corrosion	1
Pesticide and Herbicide Use	3
Industrial and Petroleum Spills or Dumping	3
Leakage from Underground Tanks	3
Harmful Chemical Constituents in Springs	3
Changes in Water Table	3
Changes in Cave Drip Waters	LD
Vegetation Removal	2
Species Richness of Cave Biota	LD
Population Density of Cave Biota	LD
Species Richness of Groundwater Biota	LD
Population Density of Groundwater Biota	LD
Destruction or Removal of Historical Artifacts	1
Regulatory Protection	1
Enforcement of Regulations	3
Public Education	1
Building of Roads	3
Building Over Karst Features	3
Construction Within Caves	1
Total Indicator Score (A)	50
Total Possible Score Including LD's (B)	93
Total Possible Score Excluding LD's (C)	72
Level of Disturbance (A/B)	0.54
Level of Disturbance (A/C)	0.69

Degree of Disturbance: Arecibo, Puerto Rico

Two scores were calculated for the purpose of identifying potential refinements. The original method counts LD's in the highest possible score, thus, significantly altering the total score. A second calculation was used that excluded the LD's in the highest possible score. A total indicator score of 50 out of the highest possible score of 93 (LD's included) was determined for the Arecibo municipality in Puerto Rico, resulting in a total karst disturbance score of 0.54. This value signifies a significantly disturbed karst area in the refined scoring classifications by North (2007). Including LD's in the highest possible score means an indicator is being represented by a 0 (No disturbance).

The second calculation takes the total indicator score of 50 out of the highest possible score of 72 (LD's excluded). This results in a total karst disturbance score of .69 for the Arecibo municipality in Puerto Rico. This score is just below the value needed to signify a critically disturbed karst area, however the score is still within the range of a severely disturbed karst area. This scoring method precludes the effect the LD's have on weighing down the total score with what equates to assigning the LD indicators with a score of 0 (No disturbance). The issues concerning the scoring techniques will be discussed in greater detail in the Chapter 5 (Discussion).

Of the thirty-one indicators, seven received a 'Lack of Data' designation: Stormwater flow into sinks, Infilling of sinkholes, Changes in cave drip waters, Species richness of cave biota, Population density of cave biota, Species richness of groundwater biota, and Population density of groundwater biota. In accordance with the determination of the level of confidence score by van Beynen and Townsend (2005) a score of 0.1 or lower signifies a high degree of confidence in the total KDI score, where as a score greater than 0.4 implies a low confidence and that more research is needed for the application KDI to yield a plausible score from assessment. Seven of the thirty-one indicators lacked sufficient data to be assessed, resulting in a level of confidence score of 0.23 that signifies a generally high degree of confidence in the KDI score for Arecibo.

Scoring of Disturbances for Modified method

The following is a detailed description for the rationality of each assessment of the disturbance scores for Arecibo, Puerto Rico based on the slightly modified KDI by De Waele (2009). This method focuses on assessment of individual disturbances on karst terrains without using indicators and subsequently ‘Lack of Data’ designations. Disturbance scores are justified using corresponding indicator data utilized in the original method; however, new or different disturbances will be justified using new acquired data. For multiple disturbances, the data were disaggregated from original methods discussion and applied to the individual disturbances. Data and discussions from the previous method are utilized for the assessment of certain disturbances due to their similarity.

Mining- The assessment of this disturbance is based on the number of mines within the study area. USGS GIS data (2005) was obtained from the Mineral Resource Data System, which contained points and descriptions of quarry/mine types. In Arecibo, there are three metal mines (gold, iron, and silica) (Figure 8). This type of disturbance is localized to three areas and is considered not to be severe, thus a score of 1 is given.

Quarrying - Quarry data was obtained from the aforementioned source and was correlated with observed quarries from fieldwork and were large and open. In the study area, there are 32 general limestone quarries, five stone and crushed/broken limestone quarries, and eight sand and gravel limestone quarries. Altogether there are 45 quarries present within Arecibo. This is a widespread and severe disturbance for the study area. Additionally, through fieldwork observations, evidence on quarry outcrops of damaged and destroyed solution conduits and potential cave passageways were found at four of the visited quarries (Figures 8 and 9)

Great Infrastructure: Hydroelectric Dam - In south-central Arecibo, Dos Bocas hydroelectric dam and reservoir alters karst hydrology and unnaturally floods the river valley (Figure 10). This human-built structure was constructed in 1942 and is the second largest hydroelectric dam in Puerto Rico and spans 30,420 acre-feet (Hunter 1995; Soler-López 2007). The original storage capacity was 37.5 million cubic meters, which was reduced by more than half, holding 17.26 million by 2005 due to high sedimentation. The drainage area for the dam was reduced from 440 square kilometers to 310 in 1948 with the construction of the Lago Caonillas Dam (Soler-López 2007). This human-built structure is a significant and severe disturbance to karst on a meso-scale that alters the natural hydrological recharge downstream and can contribute to salt water intrusion along the coast and changes in the water table. For this reason, a score of 3 is given for this disturbance.

Great Infrastructure: Radio Telescope - One of the sinkholes in Arecibo houses the world's largest radio telescope, the Observatorio de Arecibo (Figure 12). The large sinkhole was utilized for its natural concave structure; however, considerable alteration was made by blasting and construction at the site. Moreover, the structure alters local hydrology by funneling all of the rainwater in its catchment area to the ground by way of rectangular outlet at the bottom of the dish. The observatory was visited during fieldwork where photos of the construction process were viewed that showed the extent of alteration to be significant, however, only at a localized level. Additionally the Camuy River runs underground the site and could have additional impacts. However, the damage is no longer severe after the original alteration. Thus, a score of 1 is given for this disturbance (Figure 12).

Irrigation Canals - In the northeastern region of Arecibo, the country's largest wetland, the Caño Tiburones is irrigated for crops and since 1949 has been pumped dry for recovery of land for agricultural use (Figure 11) (Gardiner et al. 2007). Commercial scale rice farming began in 1980 and accounts for 6,000 acres in Arecibo located in and around the wetland (Roman-Mas 1988). However, in 1998 the area was designated as a natural reserve by Puerto Rico Department of Natural Resources and a portion of the wetland is allowed to flood and is no longer pumped dry (Gardiner et al. 2007). However, the alteration and continued pumping is a widespread and high disturbance resulting in a score of 2.

Dumping Refuse Into Sinkholes - Within the study area, fieldwork was performed with the intention of indexing and assessing the state of every existing sinkhole. The majority of the terrain is logistically unfeasible to traverse, covered with dense vegetation along with obstructed views by mogotes, and also privately owned. Therefore, visiting a large percentage of the sinkholes was beyond the scope of this work. Twelve sinkholes were found and groundtruthed using a convenience sampling method. Six of the sinkholes contained refuse observed within them at differing degrees of severity from commercial containers and wrappers, such as paper, cardboard boxes, food wrappers, to large drums, refrigerators, microwaves, televisions and other household appliances, tires, and rusted automobile parts. Observations would suggest that dumping of refuse into sinkholes is largely dependent on access to the features and proximity to houses and roads. The majority of sinkholes are located between dense mogotes that are far from most people and are virtually inaccessible. For this reason, a score of 1 is given for this disturbance.

Deforestation/Vegetation Removal - The assessment of this indicator is based on the percent of urban and agricultural lands using USGS land use/land cover data of the study area in addition to tree canopy cover. Canopy cover of the study area derived from USGS's National Land Cover Database NLCD can be utilized to estimate the percentage of forested land by dividing the number of total pixel values (30m pixels) by the total number of pixels for the study area (Figure 31). This results' calculation show that approximately 48% of forested lands remain in Arecibo, based on the canopy cover, and approximately 46%, based on the land use/land cover data using a similar calculation (Figure 30).

From this, a conclusion can be derived based on the reasonable assumption that most of the land cover in the tropical study area would have been forested before settlement in 1556. However, herbaceous lands can be natural in origin or can result from anthropogenic changes, such as, lands recovering from deforestation, clear cutting, abandoned cropland, nutrient loading, and invasive species (Papp 1984; Sohn et. al. 1999). In the study area, approximately 23% of the land cover is herbaceous and was assumed in this study to be recovering lands from anthropogenic changes because of the pixels (units that represent the land cover in raster images) are in close proximity to pixels that represent anthropogenic factors (i.e. developed, agricultural, etc.). Aggregation of the natural land cover of emergent herbaceous wetlands, open water, shrub/scrub, and woody wetlands accounts for approximately 8% of the study area which was removed from the total amount of land cover that could possibly be forested. Assuming that about 92% of the land cover of Arecibo would have been forested before settlement, 46-48% remains forested resulting in a 48-50% loss in original vegetation cover for the study area due to anthropogenic factors. Thus, a severe disturbance is indicated by the data resulting in a score of 3.

Agriculture - The score was determined from the percent of land covered by this agricultural activity using a 2003 USGS land use/land cover as used in the previous indicator. Agriculture accounts for about 9% of the land use for the study area (Figure 13, 31). This disturbance is assessed to be localized and not severe resulting in a score of 1.

Urbanization - The score was determined from the percent of land covered by urban land cover using a 2003 USGS land use/land cover as used in the previous disturbance. Urbanization accounts for about 14% of the land use for the study area (Figure 13, 31). Urbanization alters the environment in more pronounced ways than other practices and accounts for a large percentage of the study area and is a widespread high disturbance. Moreover, roads, an urban component has a severe disturbance to the area, due to the number of roads and the large scale removal of mogotes for construction of several roads/highways (see *building of roads* disturbance below). Thus, a score of 2 is given for this disturbance.

Cave Vandalism - In Arecibo, the number of vadose caves are unknown; however, two tourist caves (Cueva de la Ventana and Cueva de los Indios) are present in the study area and receive high traffic. Cueva de la Ventana (The Window Cave) is very well known because of its lookout into a karst valley (Figure 16) but has no tourist infrastructure around or within it like the Río Camuy Cave to its west. This cave was visited in January of 2010 during fieldwork to document decoration removal and vandalism in the cave. Some decoration removal evidence was present along with numerous examples of vandalism by carving and graffiti (Figure 17). Cueva de los Indios (Cave of the Indians) was also documented during fieldwork and contained numerous examples of carving and graffiti both from Indian petroglyphs and by present-day tourists (Figure 18). However, due to the type of cave (sea cave) there were no formations/decorations to be removed or destroyed. Along with the tourist caves, two other non-touristic caves and three shelter caves were documented. Four additional caves were uncovered through surveys from experts and local cavers and were considered pristine. Of the eleven caves, five had decoration removal, vandalism, or both, accounting for approximately 45% of the caves. Although vandalism and destruction was documented in a large percent of caves, a score of 2 is given due to the lack of severity in these disturbances.

Sediment Removal - Guano mining is the removal of bat fecal material. It is a natural organic source of cave sediment that is considered in this indicator. Guano mining is prevalent in Puerto Rico caves and has been most prevalent in Isle de Monas' flank margin caves (Frank 1998). The Camuy cave is nearby on the boarder of Camuy and Hatillo municipalities and was not heavily exploited for its guano (Nieves-Rivera 2003). However, in Arecibo guano removal was widespread and was mined in almost every cave

(Vale, personal communication, 2010). Other resources such as minerals found within caves and cave sediments that are commonly mined are not removed in the study area. Thus, the score of 1 is given for this indicator.

Tourist Cave - Two tourist caves Cueva de la Ventana and Cueva de los Indios are present in the study area and receive high traffic. These two tourist caves have little (several rock steps added) to no construction or modification, thus, a score of 1 is given for this disturbance.

Pesticide and Herbicide Use - Synthetic and natural pesticides/herbicides utilized for agricultural practices along with dumping, infiltrate into soils and groundwater impacting the health of ecosystems and people. According to Colegio De Agronomos De Puerto Rico website; “Seven of the nine most contaminated sites in Puerto Rico are in the karst district Arecibo…”(Rosaro 2003, p. 1). Within the study area pesticide and herbicide contamination is severe due to the superfund site Pesticide Warehouse I (PWI) and is exacerbated by agricultural and residential use.

PWI facility is active and is located approximately 3 km south of the Caño Tiburones and since 1953 has prepared and stored pesticides, insecticides, herbicides, and fertilizers for use on pineapple crops in the surrounding area (Gardiner et al. 2007). Samples from groundwater and soil collected in 1996 and 2003 were analyzed (Gardiner et al. 2007). Two pesticides, heptachlorepoxide and dieldrin, were detected in the groundwater and exceeded screening guidelines. Heptachlorepoxide at maximum concentration exceeded the Ambient Water Quality Criteria (AWQC) by one order of magnitude and dieldrin at maximum concentration exceeded it by four times. Nine pesticides, aldrin, endrin, heptachlor, toxaphene, 4,4'-DDD, 4,4'-DDE, 4,4'-DDT, gamma-BHC (Lindane), and heptachlor epoxide, were detected in the soil. However, no screening guidelines are available for comparing the maximum concentrations found for these pesticides (Gardiner et al. 2007). Moreover, as stated above, these chemicals have been used on pineapple crops in the surrounding area increasing the amount released into the environment.

Additionally, another study found low levels of pesticides, primarily composed of dieldrin, heptachlor, and 4,4'-DDE, in the Lago Los Bocas reservoir on the other side of the study area to the South (Neal et al. 2005). This shows a widespread macro level impact of pesticide, herbicide, and insecticide use on the study area with high concentrations located around superfund site PWI. The data signifies a widespread a severe disturbance resulting in a score of 3.

Illegal Dumping of Industrial Waste - The EPA added the Pesticide Warehouse I (PWI) site to the Superfund National Priorities List (NPL) on September 27, 2006 because hazardous chemicals were found in the soil and ground water. The warehouse stored and prepared pesticides with excess pesticides being disposed of on the ground where leachate from the waste contaminated the soil and ground water. Clean up of this site is further complicated "due to the complexity of karst terrain hydrogeology at the site…" (USEPA 2008, p. 5).

Several other Superfund sites are listed and include: The Murcielago Pesticide Warehouse site, Finca Las Lizas site, Cambalache National Forest site, and the mitigated Pharmacia, and Upjohn Caribe Incorporated site. Contaminants for the above Superfund sites are not specified; however, due to their status as a Superfund site and the number present within the study area a score of 3 is given for this disturbance.

Illegal Dumping of Refuse – Throughout the study area, dozens of clandestine and illegal dumping locations were documented on arterial roads. These illegal dumping sites were large in a number of cases and were observed to be places where a number of scavengers picked over the assortment of refuse. The refuse included everything from large appliances, such as stoves, refrigerators, car parts, to batteries and household garbage. In one location, refuse was dumped under and across from a "No Dumping" sign (Figure 23). As stated in Hunter & Arbona (1995): "Plastic bags of noxious household refuse, washing machines, refrigerators and derelict motor cars can be seen abandoned on mountain roadsides, in ravines, pushed down limestone sinkholes, or tipped off bridges into rivers" (p. 1340).

The amount of occurrences and volume of refuse observed during fieldwork was staggering and deleterious to the environment on a large scale. For the aforementioned reasons, this disturbance is widespread and severe and given a score of 3.

Legal Dumping of Industrial Waste – The Toxic Release Inventory system through the EPA monitors and receives reports of dumping of industrial waste for a number of industries. Another monitoring system through the EPA lists the industries that are known to produce hazardous wastes. Utilizing these systems Arecibo has 8 Toxic Release sites 64 Hazardous Waste sites (Figure 21) that release chemicals in different quantities. Seven of the companies along with details of the released pollutants are shown in the following table (Table 4).

Table 4. Industries that Release Chemicals in Arecibo

Company	Releasement Media	Year	Chemicals
Pharmacia & Upjohn Caribe Incorporated	AIR FUG, AIR STACK and OTH DISP	1998-2008	Acetonitrile, Ammonia, Benzo (G, H, I) Perylene, Cyclohexane, Dichloromethane, Ethylene Glycol, Formaldehyde, Mercury, Methanol, Methyl Ethylketone, N, N- Dimethylformamide, N- Butyl Alcohol, N-Hexane, Polycyolic Aromatic
Kayser Roth Hosiery Incorporated	Released into receiving streams or water bodies	1993, 1994	Ammonium sulfate (solution)
Puerto Rico Electric Power Authority Cambalache Combustion Turbine Plant	AIR FUG , AIR STACK and DISP NON METALS, RCRA C	1998-2008	1,2,4-Trimethylbenzene, Ammonia, Copper Compounds, Lead, Lead Compounds, Mercury compounds, N-Hexane, Naphthalene, Polycyclic Aromatic Compounds, Sulfuric Acid
Thermo King De Puerto Rico	AIR FUG and AIR STACK	1998-2009	Chromium, Ethylene Glycol, Xylene (Mixed Isomers)
Maycom Amp Puerto Rico Incorporated	AIR FUG	1989-2008	1,1,1-Trimethylbenzene
Cutler Hammer Electrical Company	AIR FUG, AIR STACK, and DISP NON METALS, RCRA C	1998-2000	Aluminum Oxide (Fibrous forms), Copper, Cyanide Compounds, Formaldehyde, Nickel Compounds, Phenol, Silver Compounds, Styrene, Zinc Compounds
Merch Sharp & Dohme Quimica De Puerto Rico	AIR FUG and AIR STACK	1993-2008	Acetone, Naphthalene, Sulfuric Acid

Legal Dumping of Refuse - Arecibo has a large regional landfill that is located less than 30 meters away from Puerto Rico's largest coastal wetland the Caño Tiburones (Figure 11). Estimates by the Solid Waste Management Authority projected that by 2000 the solid waste of Puerto Rico would be 6,684 tons a day, and 59% will come from 12 of the 76 municipalities. The municipality of Arecibo ranked 8^{th} in tonnage of refuse produced (Hunter & Arbona 1995). The majority of refuse is deposited in the regional landfill. Measurement of the landfill using orthoimagery in ArcMap revealed that it covered approximately 206, 304 square meters of area and its height exceeded 4 meters for most of the area. Additionally, fieldwork revealed that some of the refuse from the large mound find its way into the wetland and leachate is assumed to infiltrate into the wetland water due to its close proximity and natural drainage processes. The size of the landfill coupled with volume of refuse deposited and location to a wetland ecosystem presents a widespread and severe disturbance and is given a score of 3.

Leakage From Underground Tanks - According to a press release by the EPA (2010), "Petroleum release from underground storage tanks can contaminate water, making it unsafe to drink, pose fire and explosion hazards, and can have short and long-term effects on people's health" (p. 1). In June of 1998, the Puerto Rico Land Authority (Autoridad de Tierras de Puerto Rico) agreed to properly remove all underground storage tanks on the island and pay $50,000 penalty for violations of federal regulations (Cahill 1998). In Arecibo, one filling station failed to have leak detection provided and was cited for this violation in May of 1997 (Cahill 1998). Upjohn Facility had a severe underground tank leak listed on the National Priorities List and designated a superfund site in 1984 (EPA 2010). The primary pollutants of concern were Volatile Organic Compounds (VOC's).

Leaking Underground Storage Tanks (LUST) are reported and made public in Puerto Rico by the Estado Libre Asociado de Puerto Rico, Oficina del Governador: Junta de Calidad Ambiental-División de Protección de Aguas Subterraneas. The system that oversees the underground storage tanks are delegated by the federal EPA. A LUST list obtained from the site above has twenty-seven listed leaking underground storage tanks in Arecibo ("lust list" 2007). This signifies a widespread severe disturbance and is given a score of 3.

Pumping - The municipality is heavily urbanized and dependant on freshwater from the aquifer. In 1980, daily withdrawals from the groundwater accounted for 43% of the water consumed in north and south coast aquifers and totaled 210 million gallons a day (mgd) (Hunter & Arbona 1995). Gomez-Gomez (1987) divided the Arecibo municipality by the principal aquifer and withdrawal zones A (west coast to Río Grande de Arecibo) and B (Río Grande de Arecibo to Río de la Plata). In zone A, five mgd were withdrawn accounting for 11.1 % of the groundwater. Zone B was one of two zones that dependence on groundwater was the greatest and had 60 mgd withdrawn accounting for 92.3% of the groundwater (Hunter & Arbona 1995, Gomez-Gomez 1987). The amount of heavy pumping has increased the loss in the aquifer due to saltwater encroachment in Arecibo (Hunter and Arbona, 1995; Zack et al. 1988). USGS (2006) potentiometric maps are available for part of the study area; however, no previous maps are available to discern any changes from previous years for the study area (Rodriques & Gomez-Gomez 2008). The disturbance of pumping is a widespread and severe problem within the study area and is given a score of 3.

Injection of Excess Streamflow - Another anthropogenic change to the water table results from injection of excess streamflow into the saline aquifer for the purpose of storing water for use when surface-waters are minimal and to help prevent the inland migration of salt water (Quiñones-Aponte et al. 1989). In a USGS water resources investigation report six injection-recovery test were made that included injected volumes ranging from 0.6 to 6.6 million gallons for storage period ranging from 6 minutes to nearly 31 days (Quiñones-Aponte et al. 1989). Although these tests were designed to understand the feasibility of injecting, storing, and recovering the excess streamflow to aid in reducing some of the harmful impacts caused by heavy pumping it affected the water table for those periods and is a disturbance. However, the impacts of this type of disturbance are unknown and could include temporally flooding karst areas that contain vadose passageways. This experiment was short lived and is not an ongoing disturbance, thus a score of 1 given.

Impervious surfaces - Imperviousness of an area can indicate building of infrastructure and other surface practices that alter hydrological processes and vegetation that can be useful in determining impacts to karst. Impervious surfaces are predominantly artificial surfaces that cover land and disallow the infiltration of water into the soil negatively impacting the environment (Arnold et al. 1996). These impervious anthropogenic structures are mainly comprised of pavements such as, concrete, asphalt, stone, and rooftop materials; however, soils compacted by urban practices are highly impervious as well (Arnold et al. 1996). Impervious surfaces caused by infrastructure alter many factors that are often deleterious to karst environments. Moreover, impervious materials cause or increase stormwater runoff that carries non-point surface pollutants into the groundwater and waterways. This is the nation's leading threat to water quality (EPA 1994). Calculations of pixel values reveal that 12.3% of the study area is comprised of impervious surfaces and is assessed to be a widespread high disturbance and is given a score of 2 (Figure 32).

Removal/Destruction of Artifacts - Historical artifacts that are destroyed or removed including petroglyphs on cave walls are included in the assessment of this disturbance. In the study area, several documented sites have had removal of historical artifacts. Two pre-Colombian habitation sites were studied and analyzed (removed artifacts) for scientific purposes (AR-38—Tanamá Site; Ar-39—Río Tanamá Site). They are located on the North side of the Río Tanamá, a small tributary of the Río Grande de Arecibo (Pagán Jiménez 2006; Carlson and Steadman 2009).

Petroglyphs are “rock carvings that can be found on river boulders, walls of caves and rock shelters, and on stone slabs associated with aboriginal ‘juegos de bola’ or dance plazas” (Frassetto 1960, p 18). Many of these artifacts have been removed by collectors and caves have also been disturbed for procurement of artifacts throughout Puerto Rico (Frassetto 1960). Cueva de los Indios is a tourist cave known for its numerous carvings and was designated a Natural Reserve in 1992 by the Planning Board of Puerto Rico (Miní 2005). Fieldwork examined these petroglyphs and found that no discernable damage has taken place and they were well-preserved (Figure 18). For these reasons the disturbance is considered localized and not severe and given a score of 1.

Road Construction - In Arecibo, there is one expressway, two highways, 39 major roads, and approximately 459 arterial streets (Figure 29). The roads collectively have a severe and widespread disturbance on karst; however, some of the roads constructed impact the karst terrain far greater than others. An example of this is PR-10, which cuts through dense mogotes where large quantities of rock were blasted away and removed to construct the highway (compare Figure 13 with Figure 29). Impacts caused by this practice are severe and by function allow other harmful practices, such as, illegal dumping to be more widespread, thus, a score of 3 is given for this disturbance.

Construction in Caves - The evaluation of this indicator is based on the percent of caves within the study area that had evidence of construction and to what degree the impact of the construction had on the cave. To establish the degree of severity the construction had on the cave, the construction had to fall into three proposed levels of severity: significant alteration to the cave (i.e. construction of walkways, enlargement of cave openings, large amount of foreign material brought into cave), moderate alteration to the cave (i.e. lights, few handrails, small amount of foreign material brought into cave), or light alteration to the cave (i.e. gates).

Of the eight documented and four other known caves (Cueva Sorbettos, Cueva Culebrones, Cueva Dos Chorros, and Nacimiento Opiolla) two had construction within them (16%) (Kambesis, personal communication, 2010). The two tourist caves of Arecibo, Cueva de la Ventana and Cueva de los Indios had no construction within the caves. Three other caves were documented with one having been gated (light alteration) and the others had no construction. Three shelter caves were also documented with one made into a shelter for storage (moderate alteration) (Figure 30). Therefore, a score of 1 is assigned to this disturbance.

Uncontrolled Caves – Caves within the study area are largely uncontrolled and not monitored by any person or group except for Cueva de los Indios and one cave on private property that is gated. Cueva de los Indios is privately owned and therefore is monitored, although not directly by the owners (no guides or security). This lack of control yields negative impacts of vandalism in various forms. Tourists, cavers, and scientists have virtually unlimited access to most caves in the study area which have resulted in disturbances to speleothem development by way of condensation corrosion, desiccation and removal/vandalism, in addition to floor compaction, sediment removal (guano mining), and disruption to various endemic biota. Damage and disturbance to the caves as a direct result of caves being uncontrolled is not high and widespread, however, because there is no control on caves for the study area a score of 2 is given for this disturbance.

Stone Clearing – In Arecibo, mogotes are present in high densities. This particular karst formation is removed in large quantities for the construction of roads. One such road, I – 10, is bounded on both sides by large mogotes that is clearly evident of very large scale clearing of limestone (Figure 33). Moreover, two large structures were also built in the mogotes and required clearing and removal of rock: Dos Bocas Hydroelectric Dam and Observatorio de Arecibo. These activities together are a widespread high disturbance to the karst terrain byway of large-scale stone clearing and are given a score of 2.

Fig. 33 I – 10 Cutting Through the Mogotes in Arecibo, Puerto Rico (taken by Brandon Porter 2010)

Animal Farming – The practice of animal farming is present within the study area, however, the economy of Arecibo is based largely on industry related activities and therefore it is not a large-scale practice. For the assessment of this disturbance a USGS land use/land cover map was used to ascertain the percent of lands that are used for grazing in addition to fieldwork observations. In Arecibo, 5.58% of lands are used for hay and/or pasture. Fieldwork revealed that the majority of this land use is for hay and not pasture. Cattle and other farmed animals were observed but at relatively small scales (>50 head of cattle). The impact by this disturbance is localized and not severe and given a score of 1.

Sewage – In the study area, sewage disposal is an issue. A large percentage of the population relies on septic tanks or outdated inadequately developed infrastructure that is unable to properly deal with the volume of human waste (Hunter & Arbona 1995). Unauthorized domestic hookups exceed the capacities of the plants and most of the sewage facilities cannot provide treatment and raw sewage is discharged into streams (Hunter & Arbona 1995). Fecal coliform counts were greater than 10,000 colonies per 100 ml of sampled surface water in Rio Grande de Arecibo (Hunter & Arbona 1995). In addition, flash flooding occurs with every major precipitation event resulting in sewage discharges into the environment from non point sources. During fieldwork stormwater runoff and flash flooding was observed in multiple areas. One location was documented that showed large amounts of sewage (identified by smell) flushed out from under a road from a stormwater runoff entry culvert (Figure 34). Further investigation into other problem sites was limited by visibility, duration of flash flooding, and logistical infeasibilities. For the aforementioned reasons, a score of 2 is given for the study area.

Fig. 34 Picture: Sewage Flushed Out From Under a Road from a Stormwater Runoff Entry Culvert (taken by Brandon Porter 2010)

Degree of Disturbance for Modified KDI Method

The disturbance scores for each disturbance for the study area with brief justification are shown in Table 5.

Table 5 Summation of Disturbance Scores for Arecibo

Disturbance	Score	Justification
Quarrying	3	45 quarries present
Mining	1	3 quarries present
Great Infrastructure: Dam	3	Large dam alters karst hydrology and sediment recharge
Irrigation Cannels	2	Cannels cover large area and alter hydrology
Dumping of Refuse into Sinks	1	Majority of sinks are located in inaccessible terrains.
Deforestation	3	48-50% loss in original vegetation cover
Agriculture	1	Agriculture accounts for about 9% of the land use
Urbanization	2	Urbanization accounts for about 14% of the land use
Cave Vandalism	2	45% of the caves had vandalism
Sediment Removal	1	non-industrial guano mining in the past
Tourist Caves	1	Two tourist caves with no infrastructure
Pesticide and Herbicide Use	3	Superfund site coupled with use on agriculture
Illegal Dumping of Industrial Waste	3	5 superfund sites
Illegal Dumping of Refuse	3	Documented cases during fieldwork were numerous
Legal Dumping of Industrial Waste	3	8 toxic release sites; 64 hazardous waste sites
Legal Dumping of Refuse	3	Landfill (approximately 206, 304 square meters) next to a wetland
Leakage from Underground Tanks	3	24 known leaking underground tanks
Pumping	3	92.3% of the groundwater withdrawn in a zone of Arecibo
Injection of Excess Streamflow	1	injection-recovery test injected volumes from 0.6 to 6.6 million gallons
Impervious Surfaces	2	12.3% of the study area is comprised of impervious surfaces
Destruction/Removal of Artifacts	1	Few instances of this disturbance
Road Construction	3	1 Expressway, 2 highways, 39 roads and approximately 459 arterial streets
Construction in Caves	1	16% of caves has little construction
Great Infrastructure: Radio Telescope	1	Largest radio telescope that altered large sinkhole
Uncontrolled Caves	2	No control on caves for the study area
Stone Clearing	2	Mogotes are removed for various infrastructures, such as roads.
Animal Farming	1	>50 head of cattle observed in a few animal farms
Sewage	2	Sewage is discharged into streams and large colonies were found in samples

Degree of Disturbance: Arecibo, Puerto Rico

For the study area, 28 disturbances to karst were assessed. A total disturbance score of 57 out of the highest possible score of 84 was determined for the Arecibo municipality in Puerto Rico, resulting in a total karst disturbance score of 0.68. This value signifies a severely disturbed karst area using the refined scoring classifications by North (2007).

Participant Interviews/Surveys

Interviews were conducted to provide information about the utility of the KDI and surveys were conducted to obtain data that was used to augment assessment of both methods. Of the five informants, all were surveyed and two were interviewed. The interviews were conducted to augment information obtained by eight interviews conducted by North (2007). One informant is a scientist for the USGS (informant A). The second informant has administrative duties for a local NGO, Citizens for the Karst (informant B). The third and fourth informants are karst scientists and surveyors (informant C and informant D). The fifth informant is a local caver and cave enthusiast (informant E).

All surveyed informants provided useful information and qualitative data that was used in the assessment of indicators/disturbances. The information obtained from these informants was not contradictory in anyway. Moreover, most observations made by them for various indicators were correlated with fieldwork observations and by each other's responses. In instances where they had not observed the disturbance they confessed that they did not know. Some informants supported what they reported by offering details of specific locations and dates pertinent to their observations, perhaps demonstrating more familiarity and less subjectivity. Additionally, informant B identified the local guano mining disturbance that was not found through literature searches, and helped assess the *Mineral or Sediment Removal* indicator.

Interviews with informant A and informant B were conducted and an abbreviated description of the information obtained from them is discussed here. Both informants report that they incorporate knowledge of karst into their work. Informant A uses this knowledge in scientific studies conducted through USGS. Informant B uses this knowledge for legal advice, consulting (municipal and federal), and public education through affiliated website. Neither informant had any formal training or education in karst science but have many years of experience. When asked if they would find the KDI useful in their work both informants fervently agreed. Both informants reported that it would be a useful planning tool, and informant B qualified his statement by saying that it would need appropriate data. Moreover, informant A reported that when he assesses a hydrologic basin and establishes a priority for these basins, he only considers about 9 parameters in these assessments, but he concludes that these are minimal and do not include the data from impacts. Informant B reported that for the tool to be more useful it would need to emphasize the hydrology indicators because people need to understand how these impacts affect them in order to convince people to change. The informant admits to a bias towards water quality but reiterates that impacts to the karst terrain need to be assessed in a way that incorporates how these impacts adversely affect humans in order to illicit appropriate responses. Informant A was not asked this question due to the unfamiliarity with the index.

Both informants have an understanding of the differences in qualitative and quantitative data; however, informant A incorporates mostly quantitative data in his work. The informants agree that quantitative data is most valuable and that qualitative data should be minimal, but used for certain things (informant A) and used for quick assessment (informant B). Moreover, informant A stresses the subjectivity of qualitative data and would not support a large extent of work with qualitative data work. Informant

A reported that he primarily uses quantitative data in his research and tries not to mix qualitative data with it. However, informant B uses both as needed.

Chapter Five

Discussion

Anthropogenic Disturbance on Karst in Arecibo, Puerto Rico

The application of the original KDI method with refinements by North (2007) revealed disturbances to the karst environment in Arecibo with varying degrees of severity. Application of the modified KDI method by de Waele (2009) provided similar results, but with a higher total disturbance score. Overall, levels of disturbance were high with an original method score of 0.54 (Significantly Disturbed) and modified method score of 0.68 (Severely Disturbed), respectively. The scoring classification structure by North (2007) was found to be clearer and has the added value of two more classes that better describe the state of disturbance to karst than the original classification by van Beynen and Townsend (2005) that was used by de Waele (2009). Thus, it was used on both KDI scores for consistency and its added benefits.

The application of the original and modified KDI methods both reveal karst disturbances to Arecibo, Puerto Rico, identifying harmful practices that impact the water resources, health of the ecosystem, and the human population. The data show a real threat to the karst environment by industry and urbanization. Twelve of twenty-four, or 50% of the assessed indicators in the original method were assigned the highest disturbance score of 3. Similarly, eleven of the twenty-eight (39%) assessed disturbances also received a severe disturbance score using the modified method.

In the original method, twelve of the thirteen indicators that received a severe disturbance score were a direct result of industrial activities and industry-related infrastructure. The quarrying and mining industries have 45 quarries and 3 mines in Arecibo, substantially altering the karst terrain on a macro scale. The flooding of surface karst and flooding of subsurface karst indicators' disturbance is caused by the second largest hydroelectric dam in Puerto Rico, which is used to supplement the electric industry's power. The use of pesticides and herbicides in the study area, coupled with a large spill of these various chemicals by industrial corporations, causes great detriment to the environment and quality of water. Industrial, petroleum spills, and/or dumping are other industrial practices that can cause poor water quality with adverse human health effects and are present in the study area in numerous cases. Harmful chemicals and bacteria were found in springs and wells demonstrating how pollution from various sources affects the groundwater. Leakage from underground tanks is another problem that adversely affects water quality and known cases were also numerous in Arecibo (27 known, p. 66). Changes in the water table are primarily caused by industrial usage and result in significant over pumping of the areas aquifer. Lastly, the building of roads and building over karst features indicators were related to industrial activities that have created severe impacts to the karst terrain. The only indicator that received a score of 3 that is not directly related to industrial activities is the *Enforcement of Regulations*. However, the argument can be made that even this indicator is affected by industry.

Four of the twenty-four indicators were assigned a score of 2, signifying a widespread high disturbance. Three of these are also directly disturbed by industrial activities and include the *Soil Erosion, Vegetation Removal* and *Soil Compaction* indicators. The *Decoration Removal and/or Vandalism* indicator is assumed to be disturbed by individuals or groups due to fieldwork observations and relevant data obtained from secondary sources. Similar to the previous indicator, six of the eight indicators that were assigned a score of 1 (localized and not severe), primarily received a low disturbance score because damage inflicted to these indicators was caused by individuals and not by industrial activities. These indicators are: *Dumping of Refuse into Sinks, Mineral or Sediment Removal, Floor Sediment Compaction or Destruction, Desiccation, Condensation Corrosion,* and *Destruction/Removal of Artifacts*. *Regulatory Protection* and *Public Education* indicators are indirect measures of karst disturbance and were both assigned a score of 1. However, regulatory protection can also be impacted by industries due to the influence they can have to change legislation to benefit their particular interests. Overall, the environmental costs of doing business by industries have serious impacts that are revealed by the assessed indicators.

The modified method shows a similar pattern of industrial influence on disturbances; however, the degrees of impact of the individual disturbances in several cases are not as severe. This is partially due to the disaggregation of disturbances from indicators that are assessed on an individual basis in this method. For example, the *Mining and Quarrying* indicator is comprised of two different practices that have a severe impact on the area, largely due to the number and size of quarries, but not mines. When taken individually, the data show that the mines (3) are a localized and not a severe impact, while the quarries (45) are a severe impact. This is an example of how indicators that combine many disturbances into one score can influence the outcome of the total score and will be discussed in greater detail in the comparison of methods section.

Along with disaggregation of disturbances from indicators (Original Method) used in identifying individual disturbance (Modified Method), several disturbances for the modified method were not included or more specifically addressed in the indicators for the original method and were found and assessed on their level of impact. Moreover, several indicators (Original Method) were collapsed into a single disturbance in the modified method. For example, desiccation, and condensation corrosion were combined to form the disturbance of 'Tourist Caves.' Table 6 shows how the indicators relate to the disturbances in the modified method.

Table 6. Indicators Relationship to the Disturbances in the Modified Method

Indicator (Original Method)	Adaptation	Disturbances (Modified Method)
Quarring/Mining		Quarring
Flooding of Surface Karst		Mining
Dumping of Refuse into Sinks		Great Infastructure: Dam
Soil Erosion		Irriation Cannals
Soil Compaction		Dumping of Refuse into Sinks
Flooding of Subsurface Karst		Deforestation
Decoration Removal/Vandalism		Agriculture
Mineral or Sediment Removal		Urbanization
Floor Sediment Compaction		Cave vadalism
Dessication		Sediment Removal
Condensation Corrosion		Tourist Caves
Construction in Caves		Pesticie and Herbicide Use
Pesticie and Herbicide Use		Lllegal Dumping of Industrial Waste
Industrial/Petroeum Spills/Dumping		Lllegal Dumping of Refuse
Leakage from Underground Tanks		Legal Dumping of Industrial Waste
Changes in Water Table		Legal Dumping of Refuse
Vegetation Removal		Leakage from Underground Tanks
Destruction/Removal of Artifacts		Pumping
Building of Roads		Injection of Excess Streamflow
Building Over Karst Features		Imprevious Surfaces
		Destruction/Removal of Artifacts
		Construction of Roads
KEY		Great Infastructure: Radio Telescope
Disaggregated =		*Uncontrolled Caves
Translated		*Stone Clearing
Collapsed		*Animal Farming
New *		*Sewage

Utility of KDI: Analysis of both methods and potential refinements

The application of both KDI methods helped to identify known disturbances to the karst terrain of Arecibo and aided in the identification of strengths and weaknesses of the methods to better understand how the KDI can be applied and further refined. Although data were available for the majority of environmental issues affecting karst terrain in the study area, minor issues arose during application of the original KDI methodology that were not problematic in the application of the modified KDI methodology. Issues, along with strengths and weakness of each method, are individually discussed below.

Original Method

Through utilization of the original method with added refinements by North (2007), a number of issues and/or problems became apparent. The method is composed of 31 indicators that aim to holistically assess all known anthropogenic disturbances to a specific karst area. Several indicators were unable to be scored due to a lack of data and the logistical unfeasibility of collecting the needed data. Data for some indicators were more readily available than others and some data had numerous errors that needed fixing. Various sources of GIS data for the study area proved to be the most problematic and had a number of different types of errors that were corrected and the data able to aid in the assessment.

All 31 indicators were found to be relevant to the study area and subsequently none were deleted. Seven indicators could not be assessed and were given a lack of data designation, including: *Stormwater Flow into Sinks, Infilling of Sinkholes, Changes in*

Cave Drip Waters, Species Richness of Cave Biota, Population Density of Cave Biota, Species Richness of Groundwater Biota, and Population Density of Groundwater Biota. The *Infilling of Sinkholes* and *Stormwater Flow into Sinks* indicators had data; however, they were not adequate for assessment for reasons discussed in their corresponding results section. The other five indicators had no data available (see discussion section on the above corresponding indicators) to determine a score and gathering the needed data is beyond the scope of this work. The biota indicators represent cases where data are more unique and highly specialized. Collection of these types of data mostly come from academic research and requires a great deal of time to establish significant information. The biota indicators will likely receive LD designations in most future applications of the KDI, especially for most developing countries (North 2007). Keeping the biota indicators potentially changes the total score; however, they do consider necessary components that can show the state of the karst environment and serve to bring attention to areas that could benefit from research.

Assessment for several indicators was difficult due to the variety of ways each one could be assessed and the number of disturbances that could contribute to a score, while others could more easily be assessed with only one data set. For example, land use/land cover images were used to assess *building over karst features, soil compaction,* and *vegetation removal*. Moreover, users of the KDI may find it difficult to determine when enough data are present to properly assess an indicator. This issue stems from the lack of descriptions for various types of disturbances that could score the indicators. However, due to the large number of disturbances that could impact an indicator, a detailed description for each would take a great deal of time and still would not account for how these disturbances would impact different karst terrains.

The addition of the 'Leakage from Underground Tanks' indicator by North (2007) was easily assessed and proved to be a valuable addition to the indicators because it was a severe disturbance to the study area that would not have been included in the *Industrial/Petroleum Spills/Dumping* indicator. The change of the *Algae Blooms* indicator to *Concentration of harmful chemical constituents in springs* by North (2007) also proved to be beneficial; however, it may be beneficial to also include wells because they are representative of the state of groundwater and aquifer. Moreover, spring water quality is limiting and does not take into account overall water quality for a karst area and related springsheds. For this reason, I suggest a change should be made to the indicator that includes not only springs, but also wells as previously stated, along with bodies of water, such as wetlands, rivers, lakes, and reservoirs to gain a more holistic understanding of total water quality for a karst area.

Part of the usability of the KDI is the ability to adapt it to various locations. Two unique karst features, mogotes and sea caves, were present in the study area and are only partially considered in a few existing, original indicators. Mogotes densely cover the majority of the study area. As discussed in the *Building of Roads* and *Building over Karst Features* indicators, they are removed in large quantities for the construction of roads and other major infrastructures, like the hydroelectric dam and radio observatory, as well as for housing development. Removal of these features on large scales greatly impacts the natural karst terrain for the same reason quarrying does. For this reason, I recommend the addition of an indicator that pertains to the large-scale removal of karst landforms, such as mogotes, and tower karst, due to construction practices and development. The 'Removal of Karst Features' indicator is suggested, which would account for the removal of rock that is unrelated to quarrying. Coastal karst features are unique to island karst study areas and are only partially included in the indicators pertaining to caves. Moreover, sea caves have a particular disturbance unique to them. Refuse and other pollutants that are in the ocean can be deposited in sea caves that have an active tidal component. For example, large oil spills in the ocean can have a direct impact on sea caves, but much less so on fluvial caves located inland. Moreover, unique biotas inhabit these caves, such as an observed eel and large bee hive in Cueva de los Indios during fieldwork. Other important aspects of these caves are the unique geomorphological processes that form them from brackish waters mixing zones to transgressive and regressive ocean levels (Palmer 2007). Secondary formations are not usually present in these caves; therefore, decoration removal is not applicable, but carvings and various forms of vandalism could still be considered. For these reasons, I suggest that a 'Coastal Karst' indicator be added to the index and deleted if not applicable during the application of the KDI.

Scoring of indicators can be confusing when dealing with differing types of disturbances and subsequent impacts due to semantics. The score of 1=Localized, Not Severe and score of 2 = Widespread and High Disturbance can cause difficulties in assessing a score for an indicator that has a localized, but high, disturbance. Moreover, scoring a disturbance that is localized to one area but impacts are severe and widespread can be confusing. For example, a superfund site that has a large number of harmful contaminants that have infiltrated into the groundwater at a single point source, but where plumes are far reaching. For these reasons, I suggest to slightly modify the descriptions of the scores to; 0 = No Disturbance, 1 = Low Disturbance, 2 = High Disturbance, 3 = Severe Disturbance to help reduce confusion when assigning a score. The other component to this confusion is the issue of scale.

Scale of disturbances or scale of the impacts from disturbances is not adequately accounted for in the original method. Using the same example above, a large volume spill of contaminants in one localized area can have severe impacts on a meso- or macro-scale. Another example would be changes in the water table could be severe at a micro-, meso- or macro- scale because draw down cones from single wells would differ from over-pumping of an aquifer for municipal or industrial use. Moreover, scale or extent of a specific disturbance does not always reflect the scale or extent of the damage inflicted by that disturbance. Thus, to properly evaluate a disturbance the extent of damage from the disturbance should be accounted for, since in many cases it can far exceed the boundary of the disturbance itself. For example, a dam removes rock by blasting, affecting karst features at a local level. The dam also creates a reservoir that floods karst features upstream at a meso/macro level. This same dam also alters natural hydrological flow downstream and decreases sediment recharge rates, effecting the karst environment on a macro scale. This illustrates how one infrastructure inflicts different types of damage at different scales that far exceeds the boundary of the infrastructural disturbance itself. This was not the only indicator that showed an overlap into different scales of disturbance, but also impacts from these disturbances would overlap onto other indicators as well.

Several factors found through this research need to be considered to properly assess indicators and the impact of the subsequent disturbances with more accuracy and should be identified at the onset of assessment. These factors, when applicable, include, but are not limited to: duration of disturbances, number or frequency of disturbances, distribution of disturbances, possible mitigations of disturbances, and location of disturbances. These guidelines could help users of the KDI who are not experts in karst, consider factors that have an influence on the amount of an impact a disturbance has on a terrain. Duration of disturbances is important to consider when assessing a score because some disturbances are short lived and their impact is reduced with time, while others are permanent and the damage/impact is ongoing. For example, sediment removal from caves in the study area was due to non-commercial guano mining in the past; however, this is no longer the case and the sediment or organic matter have largely reached natural accumulations in recent years. Another example is a storm that was witnessed the first night of fieldwork, where the overflowing sewers represent a single event in time that had a major impact, but that is not always present.

Number or frequency of disturbances was considered for the assessment of several indicators, which is inherently intuitive in most cases. Quarries and mines were partially given a severe score due to the large number of cases. Distribution of disturbances was also considered in many indicators including quarries and mines because it can greatly affect the impact to a karst terrain at different scales. Mitigation of disturbances also needs to be considered when assessing a score because several superfund sites and brownfields could have been properly mitigated, thus reducing their disturbance to the environment. Finally, location of disturbances was found to be very important in a number of cases. For example, one superfund site in the study area, Pesticide Warehouse 1, had a number of contaminates detected in wells up to four miles away from the site. Another example is the location of the Dos Bocas Hydroelectric dam in the south of the study area. This infrastructure changes natural sediment recharge and alters natural hydrologic flow down the municipality's largest river, the Rio Grande de Arecibo, from beginning to end within the extent of the study area, thus impacting Arecibo on a very large scale.

Modified Method

Application of the modified method was conducted more easily than the original method and has a less complicated structure. This, in part, was due to having already accumulated the data for the original method. The main advantage to this method is its simplicity and straightforwardness. Data for 28 individual disturbances were obtained and scored. The aforementioned discussion on the scoring system and additional factors for the original method that need to be considered for accurate assessment also apply to this method. Issues regarding this method are limited due to its ease of use and less complicated structure. Moreover, no notable problems arose from its application to the study area, perhaps because it was assessed after the original method. However, it lacks several benefits that the original method provides. As discussed in greater detail in the following section (*Comparison of Methods),* this method has limitations that are evident when comparing it with the original method. These include: no pre-existing structure to guide researchers toward disturbances, it does not consider indirect karst disturbances (i.e. regulatory protection), and Lack of Data designations are helpful to identify areas where research is needed and are not incorporated into this method.

Having no pre-existing structure with this method creates a potential problem when evaluators are applying it to a karst area and have little to no background knowledge. No guide for the modified method produces a significant flaw. The resulting KDI score would be skewed by the evaluators' potential lack of knowledge of karst disturbances or by their unfamiliarity with the study area they are attempting to assess. Another consequence from this problem is that if many people apply the KDI to the same area the results are likely to be different. This issue could be corrected by the advent of a list or guide of known and most frequently occurring disturbances to karst that could be compiled so that KDI users can check off disturbances they have or do not have. A detailed list of all anthropogenic disturbances would be extensive and numerous and should be narrowed down to the main impacts in a karst area. This is largely done with the original methods list of indicators.

Indirect sources of impacts are not considered in this method, which often causes the greatest disturbance to a karst terrain. A karst area with no regulatory protection and enforcement of said regulations would potentially affect all known disturbances negatively and make them more pronounced. However, measuring disturbances could still identify indirect impacts by tracing back to why the disturbance is there to begin with. For example, a karst terrain that is heavily deforested could stem from the absence of a conservation policy.

The Lack of Data designations in this method makes it easier to use but subsequently could mean that there are many disturbances observed in a karst terrain that are not put forth in a final evaluation. This would lower the confidence and potentially skew the findings. If this method is to be used it should list other known disturbances that were considered but could not be assessed for various reasons. Further analysis of this method and the original method will be discussed in detail in the next section.

Comparison of Methods

Data obtained for the assessment of both methods had various limitations. The main limitation was difficulty with obtaining data that was recently created or updated. This issue results as a consequence of one of the main purposes of the KDI: that of experts and non-experts obtaining data that are easily accessible and using them to conduct a fairly quick assessment. For example, remotely sensed images that were obtained and used in assessment of several indictors/disturbances and were compiled and analyzed in 2004 with 2001 data by the USGS, and have an additional limitation of having an attribute accuracy of 75%. However, the data were easily obtained and worked well for the initial assessment. Collecting all the information using primary data sources would go far beyond the capabilities of most evaluators and would take, in some instances, decades of research. Additionally, doing so would require expertise in many disciplines and methodologies. Therefore, the vast majority of the indicators/disturbances of the KDI will be derived from secondary sources. Due to the volume of data needed to assess the indicators/disturbances, I found that I had to utilize the data available, even though it was not current. Nonetheless, the data did show the existence and/or extent of the disturbance. In the majority of the cases, the disturbances can be assumed to be just as prevalent or have worsened with time as population and urbanization increases. Data collection is also limited by how well the researcher is versed in data mining techniques. This issue can be addressed by collaboration; that is, contacting experts for advice on sources of data in their related disciplines, such as remote sensing, GIS, hydrology, and other relevant data from reliable sources. Lastly, relevant and current data is contingent on the amount of research that has been conducted on the study area. Study areas that are not located in developed countries tend to have less available data. Language barriers can cause further complications if the study area has a different language than that of the researcher.

The two KDI methods, although similar, have differing scores that amounted to a different level of classification for overall disturbance. This was due to inherit differences in the methods. The original method is composed of 31 indicators designed to holistically measure and account for all disturbances to a karst environment, whereas the modified method is composed of any number of individual disturbances. All of these individual disturbances can be included in the 31 indicators with little to no refinements or become an additional indicator; however, measured by themselves, the disturbances can give the added benefit of being unconstrained by the indicators and are more easily assessed because data collection is easier. This is a critical difference for two reasons; first, an indicator can be composed of many disturbances and therefore can lead to inaccuracies and/or skewing of the overall total score. For example, an indicator could have four different disturbances that are all severe but only count as a score of 3, whereas if you have them stand alone they would account for four scores of 3. In this scenario, the modified version works well to address this problem because it separates every disturbance and gives them individual scores. Second, how does one accurately give a score for an indicator that has several disturbances contributing to the impacts? For example, an indicator could have 4 disturbances that are not severe on their own, but when added together could have a severe overall impact. Depending on the implementer of the original method, 4 disturbances that have localized and not severe impacts could be given a score of 1 by averaging the impacts or be aggregated to get a score of 3. The modified version eliminates this potential problem.

Another issue with the original method is the lack of data for some indicators. This is only partially resolved by giving that indicator an LD. The modified version has no need for LD's because the implementer is only assessing known disturbances. This difference has both advantages and disadvantages. The advantage to having LD designations is that it shows areas where more research should be undertaken to better understand the state of the karst area. This gives valuable information to interested individuals or groups so that they can obtain data in lacking areas for future assessment. The disadvantage to the LD designation is that it significantly alters the total score by being counted towards the highest possible score, meaning that for every LD given it equals a score of 0 (no disturbance) for the indicator. This creates a lower total score and in most cases would not represent the actual disturbance of the karst area unless all the indicators with LD's ended up having no disturbance when data became available to adequately assess them. A way to resolve this issue with the original method is to not count the LD's in the highest possible score. Not counting the LD's was also calculated and discussed in 'Degree of Disturbance and Levels of Confidence for Original Method' section. The calculation without the LD's changed the score greatly from 0.54 to 0.69, equating to a difference of one classification level of disturbance. The calculation should be more representative to the actual state of the karst area due to the assumption that the seven LD's will not be assigned a score of 0 because no other indicators were given that score. Moreover, disturbances under one indicator were found to impact other indicators due to the interconnectedness of a karst terrain, so it would reason that the disturbances to the study area would negatively impact the seven indicators. Additionally, this score is closer to the modified method's score with a difference of only 0.01 instead of 0.14 in total score, which could further indicate a better assessment of the state of karst disturbance for the study area.

Another issue pertaining to the LD's is its vagueness when determining a level of confidence score. The calculation of the level of confidence divides the number of LD's by the number of applicable indicators resulting in a score between 0 and 1. In accordance with the original method a value below 0.1 signifies a high level of confidence and a value exceeding 0.4 indicates that the findings are insufficient. The higher LD scores indicate higher degrees of uncertainty in regards to the calculated degree of disturbance. Using 31 indicators as an example, no more than 3 LD's would result in a score less than 0.1 and 13 or more LD's would result in a score just above or beyond 0.4. This scoring system seems inadequate to justify a level of confidence with only two potential scoring results. Moreover, the sheer number of LD's to get a 0.4 or greater is high (40% or more indicators not assessed) and it is this researcher's opinion that the criteria for insufficient findings should be lowered. Additionally, the level of confidence for a score of 0.2 or 0.3 is not explained. In order to resolve these issues, a modification of this scoring system should be made. Additional categories that would provide a more detailed confidence score can easily be added. I propose a scoring system where a score less than 0.1 would indicate high level of confidence. A score of 0.1 and above but less than 0.2 would indicate a moderate level of confidence. A score of 0.2 and above but less than 0.3 would indicate a low level of confidence. Finally anything reaching or exceeding 0.3 (>10 out of 31 indicators) would indicate findings are insufficient for proper assessment.

The original method's indicators attempt to account for all anthropogenic problems that could be deleterious to karst systems. This is an advantage because it forces the evaluator, who may have very little expertise in karst environments, to consider most known issues regarding karst. The modified method has no pre-existing structure to guide people toward disturbances they are unaware of, but that could be impacting their study area.

The modified method only looks at individual disturbances, consequently excluding important factors that impact a karst region, such as regulatory protection, enforcement of regulations, and public education. These factors indirectly affect karst terrains in significant ways and are incorporated in the original method for that reason. This disadvantage prevents the modified method from holistically measuring anthropogenic impacts (both negative and positive) on a karst environment. However, this method is easy to understand and apply to a karst area. For this reason, it would be a useful tool for preliminary assessments which could be used to evaluate a karst terrain for the purpose of determining if a more in depth assessment would need to be conducted, involving more monetary resources and manpower.

Scale is an issue that is greatly debated in geography and related disciplines (Kuhn 1962; Freeman 1986; Jonas 2006). This issue stems from the arbitrary nature in which extents of phenomena are delineated for various disciplines. However, scale is needed to generalize phenomena's extent in order to more easily conceptualize the relationships between the phenomena and other variables. For instance, a specific disturbance to a karst terrain has an extent of damage that when measured and accounted for has an influence on the overall impact to an area. For example, large quarries have a severe impact at a micro level and dozens of quarries have a severe macro level impact.

> "Now one can think of circumstances where 'scale' in the sense of 'size' and/or 'geographic scope' can be causal in the sense that certain scalar properties of an object, process or activity make a difference to the way it operates or to the ways that groups act upon its knowledge- context."
> (Jonas 2006, p. 1).

The above quote touches upon the way in which scale also affects how groups act upon specific knowledge. It is important for the KDI to detail scales of impacts so that interested groups can make decisions based on the information. For example, micro scale disturbances can potentially be mitigated more easily and require less resources, while macro scale disturbances have a lesser chance of immediate mitigation, but could foster policy change in order to deal with the issues in the future. Thus, it can be suggested that from this study that scale matters when dealing with damage inflicted by disturbances and should be accounted for in the KDI.

Lastly, indicators/disturbances in both methods are not created equal, but are scored as if they were. For example, reason would suggest that desiccation or condensation corrosion does not alter and impact a karst terrain as severely as building of roads or quarrying/mining. Weighting of indicators/disturbances could solve these discrepancies and provide a more accurate total score that better represents the health of the karst area by accounting for the differences in damage inflicted by individual indicators/disturbances. However, quantifying weights would be very difficult due to the complexities of the disturbances, and the difficulty of understanding how impacts would differ and by how much. Weighting would more easily be accomplished using scales. A severe disturbance at a micro scale would not be as damaging as a severe disturbance at a macro scale. This reasoning is straightforward and does not require research into how damage differs by disturbance and to what degree. A modification to the KDI can be made that would account for scale of impact by disturbance, which could later be calculated with weighted values. For example, building of roads can be severe at different scales depending on a study area. To further illustrate this example, a study area could have certain disturbances that differ in scale of extent (Table 7).

Table 7 Scenarios of Scale of Impact

Scale	Score	Justification
Micro	1	small town with few roads
Micro	2	small town with many roads
Micro	3	small town with many roads and major two-lane highway
Meso	1	moderate sized city with few roads
Meso	2	moderate sized city with many roads
Meso	3	moderate sized city with many roads and 2 major highways
Macro	1	large city with roads localized to city extent
Macro	2	large city with many major roads and artillery roads into urban areas
Macro	3	large city with many roads throughout the study area and many major highways

This modification would allow an evaluator to have more options to better assess a disturbance to their study area. Other benefits would include added detail for disturbances, potentially easier assessments, and taking into account the scale of impact that a disturbance has on a karst terrain.

Proposed Refinements/Recommendations

The application of the two KDI methods revealed strengths and weaknesses in both as discussed above. The original method has a higher utility because it is more holistic, points out areas that are in need of research (Lack of Data designations), and has a structured application that will reduce subjectivity by evaluators and force them to consider disturbances of which they may not have previously been aware. For these reasons, this researcher found that original method is a better tool and that some of the strengths found in the modified method could be incorporated into this method to optimize the index.

The modified method is easy to use and understand; however, this strength creates significant weaknesses that reiterate the advantages of original method and include but are not limited to: (1) a lack of indicators that can guide an evaluator to identify potential threats to a study area; (2) LD's designations are useful for understanding what is missing in a score and shows areas were research is needed; and (3) indirect impacts to karst from regulatory protection, enforcement of regulations, and public education are not assessed. However, the advantage of assessing disturbances adds detail and aids in clearer understanding of what is impacting an area. For these reasons, it seems a compromise would be to attempt to incorporate the strengths of the modified method into the original method, while eliminating some weaknesses of the original method with additional refinements for the purpose of yielding a better KDI.

The recommendations for refining the KDI are:

- Scoring system modified to: 0 = No Disturbance, 1 = Low Disturbance, 2 = High Disturbance, 3 = Severe Disturbance. This would reduce confusion by removing words that deal with scale of disturbance (i.e. localized and widespread).
- Modifying scale column to Scale of Impact, thus allowing evaluators to assess a disturbance's overall impact to a karst terrain.
- Adding a disturbance column, thus allowing evaluators to score multiple disturbances that comprise an indicator. Unlimited amount of disturbances can be indexed. More than one disturbance can be listed in the same scale of disturbance, giving more useful information to NGO's, government officials, etc.
- Adding two more indicators to account for other types of disturbances on different karst features in an island setting that are only partially considered by the original method. Recommended indicators are 'Removal of Karst Features' and 'Coastal Karst.'
- Not including LD's in highest possible score. Thus, reducing their influence in lowering the total score.
- Modifying the LD's scoring system to include more categories for degrees of level of confidence and lowering the insufficient findings category. This way, a score of less than 0.1 indicates high level of confidence; 0.1 to less than 0.2 indicates a moderate level of confidence; 0.2 to less than 0.3 indicates a low level of confidence and any score exceeding; 0.3 and above indicates insufficient findings.

- Weighting of disturbances by Scale of Impact, which could more accurately depict the disturbance of the karst area.

In order to use weighting of disturbances by scale of impact, scale has to be defined to represent a specific extent. Although there is no set extent when dealing with geographic scale as previously discussed and revealed by literature, one could arbitrarily choose the following perception of scale for this study area: micro <1% (1.3 mi^2), meso >1% but < 20% (1.4-25.4 mi^2), macro is > 20% (25.5-127 mi^2). Weighting of indices is a complicated issue that stems from determining appropriate weighted values. Academic literature is lacking in regard to weighting of environmental indicators; however, I believe that the weighting of disturbances would more accurately measure the impacts to a karst terrain. Some examples that illustrate scenarios where impacts from disturbances differ include: One large (millions of barrels) chemical spill on the coast of Arecibo would affect a small geographic area due to the groundwater flow towards the ocean causing the subsequent chemical plume to be isolated. However, the same spill located inland and close to the southern border of Arecibo municipality would affect a much larger geographic area due to higher densities of karst features combined with a steep hydrologic gradient and a lack of a terminal or limiting process/feature facilitated by the ocean boundary, thus, allowing contaminants and their subsequent plume to extend much farther. The former spill example would be a severe, but micro-scale impact, and the latter would be a severe meso to macro scale impact, spatially. Another example of a disturbance that, depending upon different factors, could have a small or large scale but severe impact is the location of a hydroelectric dam within a study area. If the dam and reservoir are completely within the study area's extent, then it could flood subsurface karst at a meso to macro scale, depending on the reservoirs size. However, if the reservoir is partially located in the study area's extent, then the flooding of subsurface karst could be micro to meso. A final example that was discussed previously is the disturbance caused by the building of roads. A large highway cutting through mogotes is a severe micro scale impact, a dozen or more highways would be a severe macro scale impact.

Proposed weights that could be added to the overall disturbance score for each scale attempt to arbitrarily account for amount of area impacted: Micro =0.1, Meso = 0.3, Macro = 0.6. However, devising a weighting system that is not arbitrary would involve analysis of multiple KDI scores of many areas to calculate how different weighted values would affect the KDI scores, which goes well beyond the scope of this work. Nonetheless, it seems that the weighting of indices would produce more accurate scores and should be further researched. The disturbances that fall within the above criteria would undergo the same simple calculation for the total disturbance score. All disturbances under their respective scale of impact would be added together and divided by the highest possible score. The total disturbance score for that scale could then be weighted by the proposed weights, the resulting calculations would then be added together to get the final score.

The following example (Table 8) will include the proposed recommendations and refinements to the KDI, illustrating how it could be assessed. The calculations using the proposed weighting system will follow the table.

Table 8 Example of Proposed Recommendations

Category	Attribute	Indicator	Scale of Disturbance	Disturbance(s)	Score 0- No Disturbance 1- Low Disturbance 2- High Disturbance 3- Severe Disturbance	Justifications
Geomorphology	Surface Landforms	Quarrying/ Mining	Micro	3 Mines	3	Localized and Severe
			Meso		0	
			Macro	45 Quarries	3	Widespread and Severe
		Flooding (human built surface structure)	Micro		0	
			Meso	1 Hydroelectric Dam	3	Majority of Reservoir within the study area
			Macro	Irrigation Canals	1	Covers large area, however, irrigated canals are located in naturally flooded area (wetlands)
		Stormwater drainage	Micro	LD	-	
			Meso	LD	-	
			Macro	LD	-	
		Infilling of caves and/or sinks	Micro	TBA	-	
			Meso	TBA	-	
			Macro	TBA	-	
		Dumping refuse into sinks	Micro		-	
			Meso	50% of sinkholes documented had refuse	1	Majority of sinkholes are far from infrastructure and inaccessible. Low disturbance overall.
			Macro		0	
	Soils	Erosion	Micro		0	
			Meso		0	
			Macro	Land use practices	3	Urban and agriculture comprise 23% of Study area. Approximately 48-50 of forest vegetation has been removed.
		Compaction due to livestock or humans	Micro		0	
			Meso		0	
			Macro	Land use practices	3	Urban and agriculture comprise 23% of Study area
	Subsurface Karst	Flooding (human- induced flooding due to surface alteration)	Micro		0	
			Meso	1 Hydroelectric Dam	3	Majority of Reservoir within the study area
			Macro		0	
		Decoration removal – vandalism	Micro		0	
			Meso	5 of 7 caves	2	71% of caves documented had Decoration removal or vandalism
			Macro		0	

Example (calculated from Table 8)

Sum of all scores for each scale divided by highest possible score:
Micro 3/3 =1
Meso 9/12 = .75
Macro 10/12 = .83

Proposed weight to be added for overall total disturbance attempts to account for amount of area impacted:
Micro .1
Meso .3
Macro .6

Example continued from above:

Micro 3/3 =1	x .1 =	.1
Meso 9/12 = .75	x .3 =	.23
Macro 10/12 = .83	x .6 =	.50
	Total	.74

Potential Solutions for Several Disturbances

The most detrimental impacts to the Arecibo municipality are caused by industry or related to industrial activities. "…the success of the island's policy of industrialization and urbanization produces serious deterioration of the environment, and water pollution now threatens human health." (Hunter and Arbona 2007, p. 1334). Industry is highly beneficial for goods and services and is a powerful economic engine for civilizations. However, adoption of greener practices, mitigation of past disturbances, heavier enforcement of regulations, and public education can reduce the impact to our environment, which could lead to a more symbiotic relationship that would be healthier for people and be sustainable.

The data suggest the most important area for improvement is public education. Although the indicator received a low score due to a number of programs and individuals that help provide information to the populous, there exists a need to expand these programs so they can reach more people and foster greater efforts of protection and conservation. If public awareness was high enough, significant changes would occur in many areas throughout the study area (Tilbury et al. 2002). For example, illegal dumping of refuse was a severe and widespread practice that could be curbed by the knowledge of how harmful leachate from the trash easily infiltrates the aquifer that is later used for drinking water and agriculture, and affects the health of food sources, like fish. Moreover, education of sustainable practices could greatly reduce the amount of refuse in landfills and could even encourage individuals to recycle for extra money (Tilbury et al. 2002). Public education would also influence policymakers through voters' demand to stop some harmful industries and their expansion into protected areas from taking place (Brown 1981). Additionally, enforcement of preexisting regulations and the advent of new regulations could more easily pass through congress when backed by a large population of informed citizens (Milner 2002).

Many important regulations for Arecibo, and Puerto Rico as a whole, were brought forth and not passed due to a lack of interest or understanding of how these regulations would benefit individuals by protecting their vital resources from future harmful practices (Vale, personal communication, 2010). Moreover, if more of the population told their representatives that a bill is important to them and should become law there would undoubtedly be a higher success rate of these bills being passed (see regulatory protection discussion section (Milner 2002). Furthermore, industries want to produce products and services that have high demands. If people demand products and services that are 'greener' because they understand the benefits to themselves and the environment, this would force industries to act accordingly, instead of over-exploiting limited resources. This paradigm shift has begun to occur with the pursuit of 'greener' energies, organic produce and livestock that do use pesticides and herbicides, among many other examples seen today. However, this economic solution provides change over time. In Arecibo, local changes to problems could more aggressively be tackled by local entities that create programs that provide educational outreach programs that head off harmful practices and arrange volunteer groups to clean up refuse and infilled sinkholes.

Increased public education would help to alleviate future disturbances on karst and provide a healthier environment for future generations. Additionally, significant to severe damage is already present within the study area that in many cases can be mitigated, thus reducing harmful impacts. Superfund sites are an example of how harmful practices of the past can be reduced through mitigation by professionals. The study area has five superfund sites that are cataloged by the EPA and have entered into a program that attempts to remove and reduce as much of the chemicals as possible. However, the Murcielago Pesticide Warehouse-Prla Superfund site, Finca Las Lizas Superfund site, and Cambalache National Forest Superfund site have not undergone mitigation of contaminants. These sites have been awaiting mitigation for years and for some reason have not been a high priority and/or resources are not available to complete the mitigation process. Thus, the damage incurred is either ongoing and/or has dissipated into the environment and is diffuse. Leakage from underground tanks (27 known) is another harmful source of contaminants that can be mitigated by removal or replacement.

The Dos Bocas hydroelectric dam causes a severe impact to the karst terrain. However, this dam could be removed and natural hydrological flow and sedimentation would be restored. Although there are benefits from this dam, such as electricity generation and potable water reserves, these benefits are going to end due to sediment trapping. Lago Dos Bocas could be completely silted by 2059 and the subsequent sediment accumulation can impair the water-intake structure used for power generation and greatly reduce water availability for the North Coast Super Aqueduct (Soler-López 2007). For these reasons, the costs to the environment will soon outweigh the benefits of the dam.

Sewage contamination in Arecibo is another issue that could be mitigated to a large degree. In Puerto Rico, a USGS report with 72 sampled stations revealed that all of the water sources were in violation of drinking water standards due to the high presence of fecal coliforms and fecal streptococci (Hunter and Arbona 1995). Fieldwork also revealed stormwater flushed out sewage from a stormwater culvert in the city of Arecibo (Figure 35). The pattern of fecal pollution is worse in close proximity to urban zones, industrial parks, and residential suburbs that are not serviced by local sewage systems (Hunter and Arbona 1995). Hunter and Arbona (1995) also found that "Urbanization with industrialization has been so rapid as to create a serious lag in the provision of infrastructural services" (p. 1336). Thus, the supply of sewage overwhelms treatment capacity during intense rain events and is discharged into streams and groundwater during stormwater overflows. To solve this issue, there is a need for more infrastructure that adequately treats sewage and properly accommodates for the growth of the city, which would greatly reduce the problem it poses to human health.

Lastly, many disturbances cause irreversible impacts to the karst environment. Removal of rock and karst features by quarrying, building of roads, building of subdivisions, and building of other infrastructures can never be replaced. However, they serve as examples to show that certain practices, although necessary for development, have long-lasting effects on the karst environment. Moreover, these disturbances can be limited to a needed basis developed by policymakers and better development designs and technology could be employed to reduce the damage inflicted. For example, within the study area, a large number of arterial roads have been constructed that have little to no utility. These roads were constructed because resources were allocated to advance the municipality's infrastructure and provide jobs. However, a number of these constructed roads lead seemingly nowhere and dead-end. During fieldwork, several of these roads were observed and they were impassable by vehicles, and covered by sediment and vegetation (Figure 35). This is an example where better design plans with expertise could yield efficient roadways with high utility.

Fig. 35 Picture of Abandoned Road (taken by Brandon Porter)

Participant Interviews/Surveys

The surveyed participants provided very useful data for specific indicators and subsequent disturbances. Although data obtained through this method would in most cases be qualitative data, for this research it augmented various data sources and helped in assessment. Furthermore, information from these sources filled in some missing gaps in data. For example, four caves in the study area were indentified that were not found in any other secondary data sources. Additionally, feedback helped to focus some searches in the data mining process. I believe that experts of a karst region should be surveyed to help with assessing indicators and sublimate data when data are lacking or hard to acquire.

The interviewees agreed that the KDI could be a useful tool for assessing karst terrains. However, the participants also agree that the usefulness of the index is measured by the quality of data and whether that data is quantitative or qualitative. This researcher agrees with the participants that quantitative data should be sought first for assessment as to reduce the subjectivity of the researcher. Moreover, both participants believe that results from quantitative assessment are more valuable, and that qualitative data should be avoided and used when necessary. These interviews, along with eight interviews by North (2007), suggest a strong need by various individuals and groups, both governmental and nongovernmental, for a holistic tool that measures anthropogenic disturbances to karst terrains. One participant wanted to include how impacts to karst affect people directly in the method in order for the results to be more useful and hopefully bring about more changes that conserve karst terrains. This researcher agrees, in part, based on the experience that people become concerned when issues affect them directly and understands the need to 'sell' the KDI on the merits of how it affects people; however, the role of the KDI should not only measure disturbances that are harmful to people but also the environment. The dissemination of the results can later be easily interpreted to show why people should be concerned. Moreover, some disturbances are obviously detrimental to human health and can be focused on by parties who wish to convey specific problems.

Future Application of the KDI

Research into anthropogenic disturbances that degrade the health of the karst environment is needed so as to identify harmful practices that can be mitigated and create policies for protection and conservation. Further application of this index will potentially result in a useful tool for managers of karst areas that help them determine the amount of disturbance to their karst environment. Continued use of the index will test the utility of the methodology and potential refinements and/or modifications can result from scrutiny of the method(s) and the collaborative expertise of more individuals. Moreover, the evolution of the index through use on different karst landscapes and areas that has different types of human disturbance will lead to added indicators and refinements that will aid in the index's ability to holistically measure disturbance. Additionally, future studies will catalog the degree of disturbance to karst areas and the application in new areas will provide cases that can be compared and analyzed. Moreover, examination between different studies can result in a better understanding of the main disturbance contributors and causes. Areas that have already been assessed would benefit from the reapplication of the index in order to identify changes to the degree of disturbance through time and include new data when it becomes available. Also, through additional implementation of the KDI more examples of ways to quantifiably measure and assess different disturbances will be produced potentially reducing subjectivity.

Future application of my proposed refinements and recommendations will test their effectiveness and hopefully yield a better KDI. Moreover, research into the original, first modified, and my own modified version should be conducted to ascertain which method should be adopted and made available to policy makers and managers so that they can be used and tested outside of academic work. Most importantly, the KDI tool needs to include a step-by-step guide that explains how it works, what needs to be considered, examples of disturbances and how to assess them, potential data sources, a working table that can be filled in, and other pertinent information available. The step-by-step guide's purpose would be to expedite the understanding and application of the KDI. It would need to include a brief introduction of what the KDI is and its purpose. Moreover, it would have recommended readings about karst for those who are unfamiliar with the science or need a review on the processes and features of karst environments and how disturbances affect these environments in pronounced ways. Additionally, published studies that have been conducted utilizing the KDI will also be available for viewing so others can see what has already been done, as well as what problems and issues have arisen from its application to different areas by different people. Furthermore, key components will be outlined for consideration by those conducting an assessment in order to reduce potential biases and limit potential skewing of results. This could be facilitated by an online website that has all the necessary items to complete a KDI assessment, as well as instructional information. Results could also be uploaded to the site's database in order to catalogue karst disturbance throughout the world for further future analysis and dissemination of results to educate the public. The website could also have a forum that would facilitate discourse about future issues and problems that will arise from the KDI's application, and provide evaluators a medium through which to inquire and/or address said problems. This process will help to further the refinement and utility of the KDI by those for whom the methodology was originally created, and bring their varying perspectives together in a collaborated structure made possible by the proposed system.

Chapter Six

Conclusions

The original and modified Karst Disturbance Indices were applied to Arecibo, Puerto Rico for assessment of anthropogenic impacts to the karst environment. Through this study, the KDI was found to be a useful tool for holistically evaluating disturbances to a karst terrain. It could provide interested parties an opportunity to analyze threats to their karst environments in a standardized index that could result in fostering mitigation, protection, and education of this vital resource.

The application of the two KDI methods yielded results that evaluate the adverse affect of industrialization and urbanization on the karst terrain with an original method score of 0.55 (Significantly Disturbed) and 0.68 (Severely Disturbed) in the modified method. Moreover, the assessment of the indicators revealed the most severe disturbances from industrialization and urbanization affecting the karst terrain, including: *Quarrying/Mining, Flooding of Surface Karst, Flooding of Subsurface Karst, Pesticide and Herbicide Use, Industrial/Petroleum Spills/Dumping, Leakage from Underground Tanks, Changes in Water Table, Building of Roads* and *Building Over Karst Features.* Similarly, the assessment of the individual disturbances in the modified method showed *Quarries, Great Infrastructure: Dam, Deforestation, Pesticide and Herbicide Use, Illegal Dumping of Industrial Waste, Illegal Dumping of Refuse, Legal dumping of Industrial Waste, Legal Dumping of Refuse, Leakage from Underground Tanks, Pumping,* and *Road Construction* to be the most severe disturbances to the karst terrain. Of the applicable indicators, 77 percent had adequate data available to derive an assessment score, resulting in a generally high level of confidence in the total disturbance score for Arecibo. The modified method concentrates on known and measurable disturbances and therefore has no need for a degree of confidence.

Through application of both methods, the data revealed strengths and weaknesses in the two methodologies, and helped identify areas for refinement and recommendations. The modified method was more straightforward and easily understandable because it did not use comprehensive, generalized indicators or the Lack of Data (LD) scoring system. This makes the method less complicated, while yielding similar findings and identified threatened aspects of the study area of this research. However, this strength is also its greatest weakness, because it is not holistic and does not account for indirect impacts to the karst terrain that the attribute of stewardship of karst region indicators (*Regulatory Protection, Enforcement of Regulations,* and *Public Education*) provide. Moreover, the LD's identify areas where more research needs to be conducted in order to understand how the majority of disturbances threaten a study area as a whole. This is an important component of the KDI. Therefore, the modified method that only assesses disturbances has a high utility for fast assessment that could be used for preliminary evaluation. However, for a more in depth analysis of a karst region the original method provides the necessary components.

Overall, the original method, with modifications, is preferred, as it is a user-friendly tool that could be employed by professionals with varying degrees of experience and knowledge of karst systems due to clear guidelines for assessing each indicator and ease of calculating total disturbance score and level of confidence. Although some indicators do not incorporate descriptions for all types of disturbances that could affect an indicator's score, the index provides a way to holistically evaluate anthropogenic disturbances on a karst terrain in a standardized way that allows for future comparisons between different or similar areas. However, issues and problems with the KDI were found through its application on the study area. These problems are summarized in Table 9 followed by recommendations and potential refinements to improve the utility of the index in Table 10.

Table 9 Table Summarizing Problems Associated with the KDI

1) Difficult to evaluate sinkhole indictors due to inaccessibility in remote areas, poor resolution of remotely sensed data sources, and dense vegetation cover.
2) Lack of data for indicators lowers total disturbance score and in some instances logistically unfeasible to collect data.
3) *Industrial/petroleum spills/dumping* doesn't take into account types of spills and state of remediation.
4) The index doesn't account for scale of impacts from disturbances and locations of sites to be important factors for assessment.
5) The need to reword the scoring descriptions.
6) The KDI does not account for all of the disturbances that could affect an indicators' score.
7) Coastal karst and mogotes karst features are not incorporated well into the indexes indicators,
8) Subjectivity in scoring of indicators that have different types of disturbances not put forth in the original scoring descriptions.
9) No set extent for KDI application will result in difficult and inaccurate comparisons from areas with significantly different sized extents.
10) *Industrial/Petroleum Spills/Dumping* indicator doesn't have a scoring system that includes Superfund sites, Toxic Release Inventory sites, hazardous waste sites and clandestine dumping.
11) *Concentration of Harmful Chemical Constituents in Springs* indicator does not include data from wells and water bodies such as wetlands and rivers that could provide better assessment of the water quality.
12) The changes in *Water Table, Species Richness of Cave Biota, Population Density of Cave Biota, and Species Richness of Groundwater Biota* are examples of indicators that require temporally long observation periods to collect data that cannot be obtained easily.
13) Qualitative data is not as precise and is more open to arbitrary interpretations of the evaluator.
14) Indicators have an equal weight and do not take into account how disturbances impact a karst terrain in different degrees of severity or scale of impact.
15) LD's are vague and do not provide enough detail about the level of confidence. Additionally, the category that signifies insufficient findings is too high.

Table 10 Table Summarizing Recommendations and Potential Refinements for the KDI

1) Obtain high resolution remotely sensed images when analyzing the Infilling of Sinkholes indicator. When dense vegetation is present, rely on topographic maps or techniques that interpolate and remove vegetation cover in remotely sensed images.
2) Omit the Lack of Data designations (LD's) from the highest possible score.
3) Omit a brownfield or superfund site from assessment when it has undergone successful remediation. Encourage evaluators to list known contaminates from spills.
4) Change Scale column to Scale of Impact.
5) Change scoring descriptions to 0 = No Disturbance, 1 = Low Disturbance, 2 = High Disturbance, 3 = Severe Disturbance
6) Through the application of the KDI in this and other works will provide examples of how different disturbances can be assessed for an indicator.
7) Addition of the Coastal Karst and Removal of Karst Features indicators
8) Through the application of the KDI in this and other works will provide examples of how different disturbances can be assessed for an indicator helping to reduce subjectivity.
9) Encourage the KDI to be applied to county/municipal or related political boundaries that have relatively the same sized extent.
10) Through the application of the KDI in this and other works will provide examples of how different disturbances can be assessed for the *Industrial/Petroleum Spills/Dumping* indicator.
11) Change the *Spring Water Quality* attribute to Water Quality and include data from wells and other water bodies for holistic assessment of the corresponding indicator.
12) Encourage the use of quantitative data over qualitative data when possible.
13) Addition of a Disturbance column and the aforementioned Scale of Impact column can provide attributes that can be weighted for potentially more accurate assessment.
14) Modifying the LD's scoring system to include more categories for degrees of level of confidence and lowering the insufficient findings category.

Results from the KDI provides managers, planners, and other interested parties with data that assesses a karst terrains state of health and identifies critical disturbances which are negatively affecting the environment that could be mitigated or affected by policy changes. Re-application in the same area can be used to ascertain how disturbances are improving or worsening and provide information for the reasons that are causing/affecting these changes. In Arecibo, industrial practices and urbanization are responsible for the most severe impacts to the area. The impacts from these disturbances can be curbed through better policy and more enforcement of regulations. Moreover, the results indicate that agriculture and disturbances caused by people, such as desiccation and condensation corrosion, are not severe and not a cause for concern. Furthermore, by focusing on the main culprits causing the most severe impacts to an area, steps can then be undertaken to minimize the damage inflicted by human activities. Application of the KDI to neighboring municipalities will show how local regulations and activities affect karst terrains so that regional and state managers can better understand cause and effect of specific decisions.

In conclusion, the KDI holistically successfully measures the majority of anthropogenic impacts from disturbances on a karst terrain. Through the application of two KDI methods in the island setting of Arecibo, Puerto Rico, with its various land uses and land covers resulting from many types of practices and activities, the level of disturbance was determined, utility of indices evaluated, impacts to karst better understood, and refinements and recommendations were devised. Moreover, the refinements and recommendations would aid in creating a karst sensitivity index, which would help to isolate and identify potential areas of current and future disturbance, and aid in management of the karst environment. Through evaluation of disturbances to the study area's karst terrain, data and pertinent information can be used to address human induced impacts. The KDI provides organizations and communities with a tool that effectively assesses a karst area holistically, so that decisions regarding mitigation or policy changes affecting critical threats to karst can be made and results from the assessment can be disseminated to promote public education and foster conservation and protection of the valuable karst resource.

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Fig.36 Appendix A: Current Laws Affecting Karst.

Law No. 111, p. 384, § 4 : § 1143c states:	" It is hereby declared that it is the public policy of the Commonwealth to protect and preserve the caves, caverns or sinkholes in Puerto Rico. These are a unique natural resource because of their beautiful formations of natural materials; its fauna adapted to the subterranean environment; its archaeological and historical value; for being conductors and receptacles for subterranean water flow, and for providing a propitious environment for recreation and scientific research and investigation. The caves, caverns or sinkholes are, therefore, a legacy of nature that deserves immediate protection to prevent their irreparable damage or destruction" (12 L.P.R.A. § 1143a 2009).
Prohibitions and penalties of this law state:	" (a) Any person who voluntarily performs any of the following acts shall be guilty of a misdemeanor and, upon conviction, shall be punished by imprisonment for a term that shall not exceed six (6) months or by a fine that shall not exceed five hundred dollars ($500), or both penalties at the discretion of the court: (1) Breaks, cracks, chisels, paints, writes, marks, or in any way damages, destroys or defaces any natural material found in any cave, cavern or sinkhole. (2) Removes or carries away any natural material found in a cave, cavern or sinkhole. (3) Kills, damages, disturbs or removes any animal or plant found in any cave, cavern or sinkhole. (4) Alters the natural atmosphere of any cave, cavern or sinkhole in any way, including, but without being limited to, the burning of any material producing smoke or gases that are harmful to the animals and plants; Provided, That the fact of penetrating or remaining in a cave, cavern or sinkhole does not constitute a violation to this section. (5) Enters any cave, cavern or sinkhole carrying any kind of aerosol and other type of container having paint, stain or any other coloring material. (6) Breaks, forces, removes or damages any lock, gate, door or any structure or construction designed to prevent the entrance to any cave, cavern or sinkhole, regardless of the fact that the person does enter or not. (7) Offers for sale, exchange or donation; sells, exchanges or donates; exports, or in any other manner disposes of any natural material or archaeological evidence taken out of any cave, cavern or sinkhole. (8) Contaminates, diverts or alters in any way whatsoever the water in any cave, cavern or sinkhole. (b) Any person who voluntarily alters, removes, carries away or in any way damages any evidence or archaeological features found in any cave, cavern or sinkhole, including but without being limited to petroglyphs, pictographs, ceramics, bones or tools, shall be punished by imprisonment for a minimum term of six (6) months and a maximum of five (5) years, or a minimum fine of one hundred dollars ($100) and a maximum of two thousand, five hundred dollars ($2,500). (c) Any person who voluntarily deposits or leaves in any cave, cavern or sinkhole, any food, containers, ropes, electric batteries, carbide, papers, wrappings, garbage, rubble or any waste, shall be guilty of a misdemeanor and upon conviction shall be punished by a fine of not less than five dollars ($5) nor more than fifty dollars ($50), or imprisonment for one (1) day for each dollar not paid. (d) The development of dwellings, industries, structures and other buildings with foundations on the caves, caverns or sinkholes and subterranean rivers that may be a hazard to the health or safety of the community, the preservation of the caves, caverns or sinkholes, and would contaminate these bodies of water, without the prior authorization of the Secretary of Natural and Environmental Resources, is hereby forbidden. (e) The use of the caves, caverns or sinkholes for the construction of septic tanks, for the discharge of domestic or industrial waste and for the breeding of animals that could affect these ecosystems is hereby forbidden" (12 L.P.R.A. § 1143a 2009).

No. 292 § 4. Its purpose states:	"It is hereby established that the Public Policy of the Commonwealth of Puerto Rico is to protect, preserve, and manage, for the benefit of present and future generations, the karst physiography of Puerto Rico. It constitutes one of our most valued non-renewable natural resources for its geomorphology and for the special ecosystems that develop in it. The karst region is characterized for including, among others: karst formations, tower karst, dolines, sinkholes, trenches, caves, caverns, aquifers, underground rivers, and springs that have developed landscapes of spectacular qualities with a high geological, ideological, ecological, historical, recreational, and scenic value. The karst physiography fulfills vital functions for the natural and social survival of the Island, such as housing a large number of species of flora and fauna; storing vast underground water supplies; possessing lands of excellent agricultural capabilities, and containing a vast recreational and tourist potential attributable to its natural qualities" (12 L.P.R.A. § 1152 2009).
Prohibitions and penalties of this law state:	"Besides the administrative fine, any natural or juridical person that carries out any of the following acts without the corresponding permits of the Secretary, shall be guilty of a misdemeanor and, upon conviction, shall be punished by imprisonment for a term not to exceed six (6) months, or a fine which shall not exceed the sum of five hundred dollars ($500), or both penalties, at the discretion of the court: (a) The extraction, excavation, and removal of limestone rock for commercial purposes or for the leveling of terrain without the Secretary's authorization, pursuant to §§ 206 et seq. of Title 28, known as the "Sand, Gravel and Stone Act," as amended, and its respective regulations. No simple permits or exemptions shall be granted in the zone for these purposes. (b) The creation of dumps for domestic waste, hazardous waste, or special or industrial non hazardous waste in the karst region. (c) Agricultural activity that leads to the total extermination of the area's vegetation, or which implies a substantial reduction, be it within one of the same species, among species, or an ecosystem; the use of pesticides, herbicides, or any biocide that is not degradable by biological, chemical, or folic action, that may seep through to aquifers. (d) The construction of roads, highways, or other means of access without the Secretary's authorization, as provided by this chapter. (e) The construction of infrastructure for the enjoyment of scenic areas without the Secretary's authorization, as provided by this chapter. (f) The fragmentation of ecosystems of natural value. The term fragmentation shall include the division, separation, or isolation of any ecosystems that are intact, or that when this act is approved, has a high natural value, even though they have been fragmented in the past. The separation, isolation, and division may be caused by roads, or paths that cross them, or by remaining portions of the ecosystems to destine them for uses other than the preservation of natural systems. (g) Deforestation, selective or total, removal of native and endemic vegetation for commercial landscape design activities, and removal of live ligneous material for the generation of charcoal without due evaluation and authorization, under the provisions of this chapter, and by the provisions included in other applicable laws and regulations. (h) Removal, hunting, capture, or extermination of wildlife whose habitat is the karst region, without the proper authorization of the Secretary, as provided by this chapter. (i) The construction and installation of towers and antennas for electrical transmission lines, or antennas for communication, without due authorization by the Secretary, as provided by this chapter. (j) The creation of ecological tourism projects in the karst regions without the proper authorization of the Secretary, as provided by this chapter" (12 L.P.R.A. § 1152 2009).